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COURSE-KEEPING
WITH AUTOMATIC CONTROL

Eduardo Aguayo

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

COURSE-KEEPING
WITH AUTOMATIC CONTROL

by

Eduardo Aguayo

Thesis Advisor: G. J. Thaler

December 1973

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Course-Keeping With Automatic Control

by

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Lieutenant Commander, Peruvian Navy
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ABSTRACT

A ship in steering is considered as a physical mechanism that is forced by a rudder movement to produce a response. Emphasis is laid upon the relation between the forcing and the response, leaving aside any detailed consideration of the forces concerned.

Course-Keeping with Automatic Control techniques is studied following this concept. Computer programs are developed to simulate different conditions. Interpretation of the results is made to evaluate the different methods used.

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I. INTRODUCTION

Problems that justify the use of Automatic Control for ships:

The maneuverability of a ship is determined by the physical properties of the ship in its environment and the physiological and psychological properties of its navigator.

A successful mission of a vehicle in its operating environment is a function of its handling as well as its design. The relationship between helmsmanship and the steering system has been discussed in detail by Abkowitz [1], Brard [2], Davidson [3], Nomoto [4], among others, and the conclusions indicate that the hydrodynamic design factors alone can not significantly improve the handling qualities of ships.

The past decade will be known as the decade of the Super-Tankers. Ships were made larger for many reasons, one of which was to improve operations efficiency. To realize the full benefit of the larger size, the ship had to be steered as efficiently as possible. Almost every Super-Tanker built nowadays is course unstable and the control of such a system has been of great concern. We can see easily that it is not difficult to design an autopilot if enough rate control is available [5].

The basis for the need of Automatic Control was a minimum number of operator controls, minimum rudder orders for course-

keeping and automatic course correction without overshoot. But the main reason for this type of control is that steering an unstable ship by manual control requires a helmsman to detect a very small amount of rate of turn and to react to this in time with the proper correction.

Even though the study of man as a pilot of giant tankers is relatively young, yet it is evident that any pilot, not withstanding his experience and seamanship, has some physiological and psychological limitations relevant for the execution of his task.

Several studies carried out [6 and 7] provided us with some insight. First a purely physiological problem is a limited capacity for the perception of motion. Very slow motions cannot be perceived by human beings as is the case with the hands of a clock. To be more specific, the smallest yaw velocity human beings can perceive is about 1 minute of arc per second. The smallest just noticeable acceleration or deceleration of the yaw motion occurs when the yaw velocity is doubled or halved within 5 seconds. Analysis of ship maneuverability experiments on full-scale models revealed that tankers above 100,000 Ton. move so slowly during maneuvers that many of the accompanying velocities and accelerations are not perceptible for the man on the bridge. This means that some information which is indispensable for the correct execution of the maneuvers is not available for the navigator due to his own physiological limitations.

The inertia of large tankers also raises a problem of a more psychological nature. It is well known to pilots and Captains that there is a time lag between a rudder command and the reaction of the ship. This lag can be easily of the order of 15 seconds. Psychological research on tracking behaviour revealed that steering tasks raise difficulties when the time lag is longer than 4 seconds. Also related to inertia is the ability to anticipate motions over long time intervals. Even very simple maneuvers take a long time and should therefore be initiated a long time beforehand. It is however, very difficult to anticipate maneuvers over long time intervals as human beings have only a limited capability for extrapolation of slow motions, i.e., the navigator can hardly predict what his position will be in 10 minutes and therefore is not able to initiate the necessary correction at the required moment.

Still another factor is the ability to discriminate among the different components of the ship's motion, those due to wind, current and steering movements initiated by the pilot.

From experiences in working with the concept of the time constant of a ship, conclusions resulted in that the difficulty in steering depends largely on this parameter, since for the same statistical characteristics, the unstable ship with the small value of absolute time constant, changes its course too quickly to be followed by the human operator.

II. COURSE-KEEPING

A. DEFINITION

Course-Keeping quality is defined as the ability of a ship to keep course easily on a seaway. This is not identical to stability on course, because the former depends upon the behaviour of the steering devices as well as of the ship, while the latter is a thoroughly passive character of the ship. So the problem of course-keeping should be treated by analyzing a closed-loop feedback system composed of a ship, an automatic or manual steering control unit and steering gear. It is possible, however, to show simply that good stability on course yields a good course-keeping quality, in general, in this form:

1. A ship that is more stable on course has less occasion to deviate significantly from its course because the stimulated motion decays more quickly even with the rudder amidship.

2. A ship that is more stable on course responds more quickly to steering, so that any course deviation can be corrected more easily.

The stability on course is related to the decay of the yaw and sway of the ship with a rudder amidship after being disturbed for a short while. In the case of an unstable ship this results in a negative damping of yaw and sway. Stability on course is also related to quick

response to steering. This is of particular importance in considering the course-keeping quality of a ship.

B. STEERING QUALITIES OF SHIPS

The dynamic stability on course of an unsteered ship is measured by the number of ship lengths traveled by a stable ship, in the time required to reduce an accidental deviation from undisturbed motion in a straight line to 1/e of its initial value, the rudder remaining in the amidship position, this quantity is defined as $1/|p_1|$.

A negative value of p_1 means that the ship is dynamically stable, i.e., when a dynamically stable ship moving on straight course is disturbed slightly, it settles down on a new straight course that is close to the original one (Figure 1). The greater the negative magnitude of p_1, the more rapidly the ship settles on its new course and the closer the new course is to the original one. A positive value of p_1 means that the ship is dynamically unstable, i.e., when a dynamically unstable ship moving on straight course is disturbed slightly, it will go into a steady circuling motion, even though the rudder is held amidship.

The primary purpose of an automatic steering device, just as of a human helmsman, is to compensate for disturbances, making the ship maintain a prescribed heading and thus making it directionally stable.

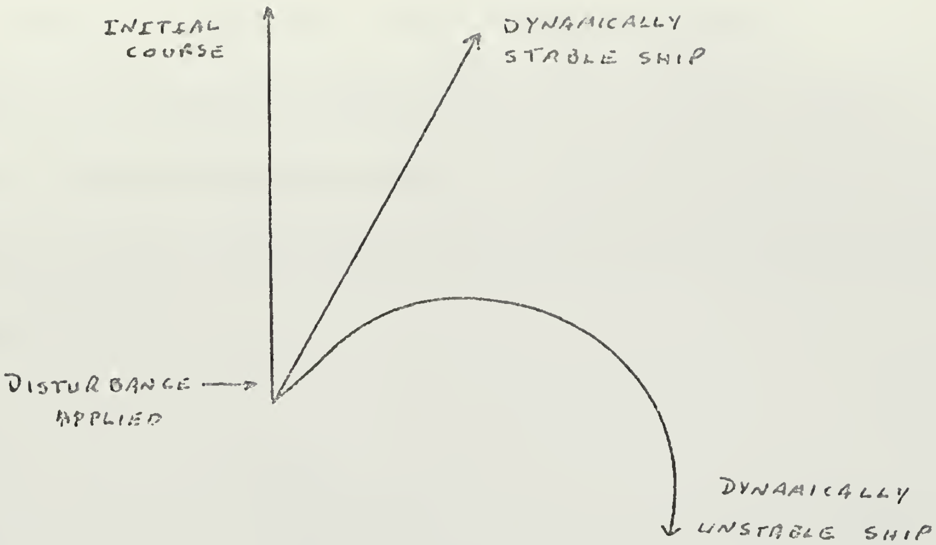


FIGURE 1

C. UNSTABLE HULL

In this study of Automatic Course-Keeping we will be working with a 200,000 DWT super-tanker of the following characteristics:

Length	310	meters
Breadth	47.16	meters
Draft	18.90	meters

Steering Quality indices:

$T_1 = -269.3$ seconds

$T_2 = 9.3$ seconds

$T_3 = 20.0$ seconds

$K = -0.0434$ rad/sec

Maximum Rudder deflection 30°

Maximum Rudder rate 2.32 degrees/second

D. AUTOMATIC CONTROL AND COURSE-KEEPING

One of the functions of ship control is to maintain a ship's heading. In performing this function, a helmsman deflects the rudder in a way which will reduce the error between the actual and desired heading (Figure 2)

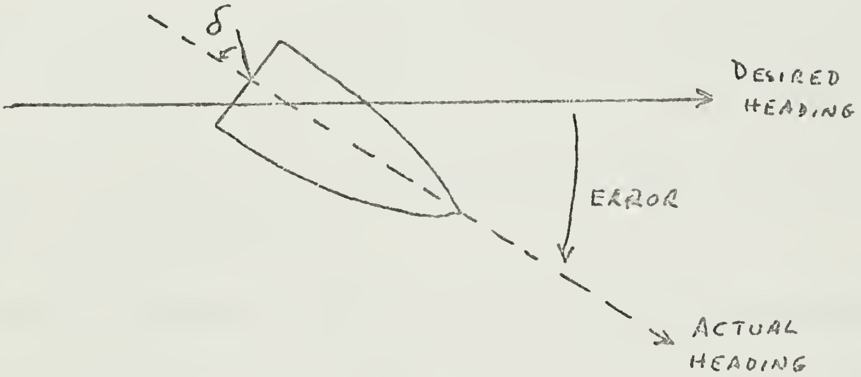


FIGURE 2

A good helmsman will not only deflect the rudder in response to the heading error, but he is also sensitive to the angular velocity of the ship and he will ease off the rudder and apply a little opposite rudder in order to prevent overshooting the desired heading. It follows that an automatic control should also be responsive to control signals measuring both error and angular velocity. Thus a rudder under automatic control might be deflected in accordance with the following linear expression:

$$\delta = -k_1 \dot{\Theta} + \delta^*$$

where

$\delta^* = k_2 \psi$ helmsman's rudder angle

$\dot{\Theta}$ angular velocity of ship

ψ heading error

The basic action of the automatic control or "autopilot" is called proportional control which means to give a helm angle proportional to the amount of course deviation and sometimes also proportional to the time rate of the deviation.

In general the complete steering system can be represented as in figure 3

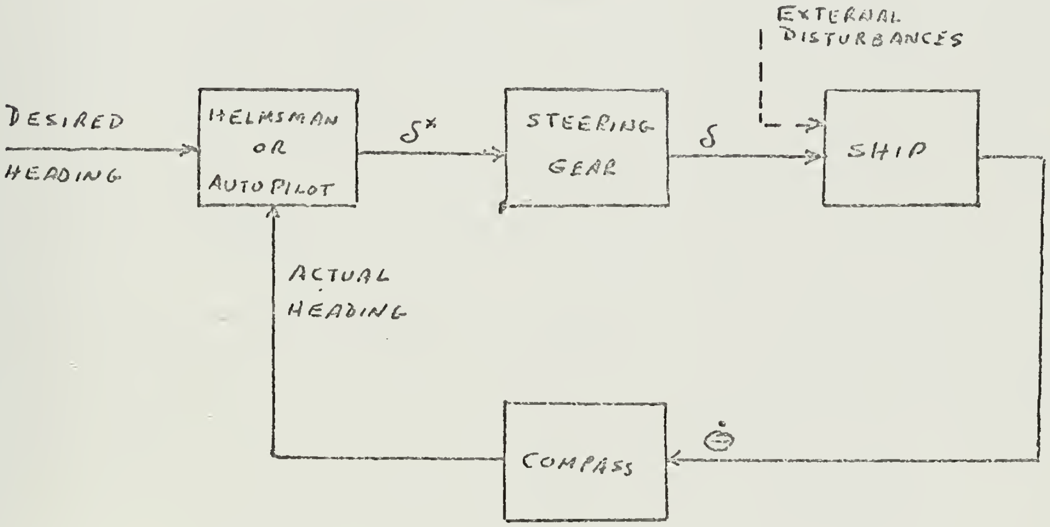


FIGURE 3

The response of a ship to steering or, the maneuverability of a ship is usually described by a set of equations of motion of side-drifting velocity and turning-angular rotation:

$$\frac{d}{dt}\begin{bmatrix} V \\ \dot{\Theta} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} V \\ \dot{\Theta} \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \delta$$

It is however, more convenient to use a single equation of motion describing immediately a relation between turning angular motion and steering, because control signals in autopiloting relates only to turning angular motion.

III. TRANSFER FUNCTION IN STEERING

The general principle of linearizing the equation of motion of a ship in steering may be summarized as follows:

1. The coupling of surging to sway and yaw is ignored because of its second-order effect on the latter motions [19].

2. Hydrodynamic forces acting upon the ship are expressed as linear functions of angle of drift, i.e., sway velocity, curvature of the ship's path, i.e., yaw angular velocity, and angle of helm.

3. Hydro-inertial forces are expressed as linear functions of the acceleration and angular acceleration of the ship.

Linear equations of motion of this kind have been introduced in a number of articles [8, 9, 10 and 17], and have proved promising in interpreting and predicting behaviours of ships in steering. In the notation used here, they are written as:

$$(L/v)\,(m' + m'_y)\,\dot{\beta} + Y'_\beta\,\beta - (L/v)\,(m' + m'_x - Y'_r)\,\dot{\Theta} = Y'_\delta\,\delta$$

$$(L/v)^2\,(I'_{zz} + J'_{zz})\,\ddot{\Theta} + (L/v)\,N'_\Theta\,\Theta - N'_\beta\,\beta = N'_\delta\,\delta \qquad \text{III-1}$$

Using these equations we can obtain the yawing (Θ (t)) and the swaying (β (t)) in response to any movement of the rudder (δ (t)).

Now limiting our interest to the steering-to-yaw response which, in general, is naturally of major importance, we introduce the

transfer function in steering. Taking the LaPlace transform of both sides of the equations III-1, we obtain:

$$-(L/v)(m'+m'_y)\beta(0)+[(L/v)(m'+m'_y)s+Y'_\beta]\beta(s)$$

$$-(L/v)(m'+m'_x-Y'_r)\dot{\Theta}(s)=Y'_\delta\,\delta(s)$$

$$-(L/v)^2(I'_{zz}+J'_{zz})\dot{\Theta}(0)+[(L/v)^2(I'_{zz}+J'_{zz})s+(L/v)N'_r]\dot{\Theta}(s)$$

$$-N'_\beta\,\beta(s)=N'_\delta\,\delta(s)$$

where $\beta(0)$ and $\dot{\Theta}(0)$ denote β and $\dot{\Theta}$ respectively at t=0, namely at the beginning of a rudder movement, and where

$\beta(s)$ is the LaPlace transform of β

$\dot{\Theta}(S)$ is the LaPlace transform of $\dot{\Theta}$

$\delta(s)$ is the LaPlace transform of δ

Taking into account the following relation at t=0

$$(L/v)^2(I'_{zz}+J_{zz})\ddot{\Theta}(0)+(L/v)N'_r\dot{\Theta}(0)-N'_\beta\,\beta(0)=0$$

we can eliminate $\beta(S)$ and $\beta(0)$ from the transformed equations [19], to yield a single equation that describes the steering-to-yaw response,[1] that is:

$$\dot{\Theta}(S)=\frac{K(1+T_3S)}{(1+T_1s)(1+T_2S)}\delta(S)+\frac{[T_1T_2s+(T_1+T_2)]\dot{\Theta}(0)+T_1T_2\ddot{\Theta}(0)}{(1+T_1s)(1+T_2s)} \quad \text{III-2}$$

---

[1] Since later in this study we are going to be dealing with automatic piloting, and the control signal under this condition relates only to turning angular motion.

where

$$K = (V/L) \frac{N'_\beta Y'_\delta + Y'_\beta N'_\delta}{Y'_\beta N'_r - (m' + m'_x - Y'_r) N'_\beta}$$

$$T_1 + T_2 = (L/V) \frac{(m' + m'_y) N'_r + (I'_{zz} + J'_{zz}) Y'_\beta}{Y'_\beta N'_r - (m' + m'_x - Y'_r) N'_\beta}$$

$$T_1 T_2 = (L/V)^2 \frac{(m' + m'_y)(I'_{zz} + J'_{zz})}{Y'_\beta N'_r - (m' + m'_x - Y'_r) N'_\beta}$$

$$T_3 = (L/V) \frac{(m' + m'_y) N'_\delta}{N'_\beta Y'_\delta + Y'_\beta N'_\delta}$$

The first term of the right side of equation III-2 corresponds to a motion excited by steering and the second to another resulting from the initial motion at t=0, the latter disappears if the ship is running straight at t=0 without any yaw or sway. Thus the rational function:

$$\frac{\dot{\theta}(s)}{\delta(s)} = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)}$$

describes the response behaviour of a ship in terms of the LaPlace transform. We may call it the transfer function of the ship in steering.

Retransforming equation III-2, we obtain a single differential equation that describes ship motion just as does the original equation of motion (Equations III-1) as far as the steering-to-yaw response is concerned, that is:

$$T_1 T_2 \frac{d^2 \dot{\theta}}{dt^2} + (T_1 + T_2) \frac{d\dot{\theta}}{dt} + \dot{\theta} = K\delta + K T_3 \frac{d\delta}{dt}$$

better known as Nomoto's Equation, this describes directly the yaw response of a ship. The four coefficients K, T_1, T_2, and T_3, which are composed of the coefficients of the original equation of motion, constitute a set of characteristic figures representing the response behaviour of the ship, they are called the steering quality indices.

A. STABILITY CRITERION OF AUTOPILOTING BY KOCHENBURGER'S METHOD

A control loop describing autopiloting of a ship is illustrated in figure 3 in the form of a block diagram. Since the stability criterion of Kochenburger [11] is based upon whether sinusoidal signals grow or decay in circulating through the loop, it is necessary first to obtain the response of each element composing the system, to sinusoidal signals.

The response of a ship to a sinusoidal signal (that is, in this case, to put a rudder sinusoidally to both sides with a certain frequency (w) may be determined through the equation of Nomoto:

$$\delta(t) = \delta_0 \sin \omega t$$

$$\dot{\Theta}(t) = A(\omega)\, \delta_0 \sin [\omega t + \phi(\omega)]$$

where

$$A(\omega) = \left| \frac{K(1 + i\omega T_3)}{(1 + i\omega T_1)(1 + i\omega T_2)} \right|$$

$$\phi(\omega) = \operatorname{Arg} \frac{K(1 + i\omega T_3)}{(1 + i\omega T_1)(1 + i\omega T_2)}$$

and where δ_0 is the amplitude of sinusoidal steering. $A(\omega)$ is called an amplitude ratio and $\phi(\omega)$ a phase difference. Both of them are functions of frequency w only, as a common feature of linear systems.

Next, the response of an electrohydraulic steering gear, which is widely used for most present ships, may be described by the following equation:

$$T_E \frac{d\delta}{dt} + \delta = \delta^*$$

where T_E is a time constant of the steering gear.

Then we get a description of the response of a steering gear to a sinusoidal δ^*, as follows:

$$\delta^* = \delta_0^* \sin \omega t$$

$$\delta = A_E(\omega)\, \delta_0^* \sin[\omega t + \phi_E(\omega)]$$

where

$$A_E(\omega) = \left| \frac{1}{1 + i\omega T_E} \right|$$

$$\phi_E(\omega) = \mathrm{Arg} \frac{1}{1 + i\omega T_E}$$

Finally, we get easily the response character of a compass as follows, because it may be considered a simple integrating element transforming $\dot{\theta}$ into θ :

$$\dot{\Theta} = \dot{\Theta}_0 \sin \omega t$$

$$\Theta = A_c(\omega)\, \dot{\Theta}_0 \sin [\omega t + \phi_c(\omega)]$$

where

$$A_c(\omega) = \left| \frac{1}{i\omega} \right| = \frac{1}{\omega}$$

$$\phi_c(\omega) = \mathrm{Arg}\, \frac{1}{i\omega} = -\frac{\pi}{2}$$

Since the transmitting character through all linear elements has been thus obtained, if a similar character of the remaining element, viz, an autopilot, is defined, we can judge whether sinusoidal signals grow or decay in circulating through the control loop. It is impossible, however. to describe the response of an autopilot by any linear differential equation and then to obtain its response character in the foregoing manner, if considering such a discontinuous element as a weather-adjust mechanism, which is used to modified proportional control in order to avoid frequent steering in practical application for rough seas.

Fortunately, however, the response itself of an autopilot with a weather-adjust mechanism to a sinusoidal input signal (that is, in this case a course deviation) may be obtained easily by expanding the response into a Fourier series with a fundamental frequency that is the same of the input signal, as follows:

$$\delta^* = C_1 \psi_0 (a_1 \sin \omega t + a_2 \cos \omega t + a_3 \sin 2\omega t + a_4 \cos 2\omega t \ldots)$$

where C_1	is the proportionality constant connecting a course deviation to a helm angle to be called for,
ψ_0	is the amplitude of course deviation, and
$a_1, a_2, a_3,$ and a_4	are the coefficients of Fourier series which may be obtained through the usual procedure of Fourier expansion if the form of δ^* is given.

Considering here that all linear elements are much more insensitive to a signal with the higher frequency, we can neglect all the higher frequency terms. This is the approximation of Kochenburger, and its validity depends upon how much the higher frequency signal decays through the linear elements and also how much higher frequency components are included in the original δ^*; viz, how much the original δ^* resembles a pure sinusoidal form. In the present case, Kochenburger's approximation may be fairly valid because a ship is quite insensitive to a high-frequency steering because of her large inertia, and also the basic action of an autopilot, even with a weather-adjust mechanism, is proportional control that produces a sinusoidal output in response to a sinusoidal input.

B. FIRST ATTEMPT TO STABILIZE THE SYSTEM

The autopilot, the steering engine and the ship with its rudder all form different components of a closed loop system, each component characterized by its transfer function or the complex ratio of output to input. The theory for such control systems and their stability has been developed in electric network engineering, and it is natural that the

dynamic problem lends itself to studies in analog computers, where each component is represented by its equivalent electric circuit. The stability of the closed loop system may be judged from the total open loop response recorded at several frequencies, without a knowledge of the individual transfer functions.

The conditions of directional stability in automatic steering along a fixed course had been discussed by Minorsky [12] by means of the technique of added derivatives, applied to a simplified one-degree of freedom oscillation and including several types of position and rate control. In 1946 Davidson and Schiff [13] took a large step towards a better understanding of the interrelation between the performance of a ship on a straight course and in turning, pointing out the nonlinearities in the behaviour of the unstable ship and including an interesting treatment of the transients when entering a steady turn. They also used linear theory for establishing a formula for the radius of the turning circle.

The work of Davidson and Schiff did much to stimulate other authors. Among many others, a paper by Williams [14] on initial stage motion and a report by Schiff and Gimprich [15], who studied an automatic control system where the rudder angle called for is proportional to a combination of heading deviation and rate of change of heading, and which has a behaviour with a close resemblance to the automatic pilots used in practice.

Most modern steering engines are designed to move the rudder with an essentially constant speed, the rudder turning at that speed as long as a control signal is transmitted to the steering engine. A gyro pilot may be used to switch on this signal, calling for a correcting rudder at a certain small deviation from the desired heading, whereas a contact on the rudder may stop the motion at a suitable angle, the rudder remains in this position until the ship has swung over to the other side of its course and the rudder is then reversed. More often a follow up mechanism assures a "proportional control" of the rudder. Due to the finite rudder speed, these systems may be self exciting, however, and excessive oscillations may be built up.

In order to overcome these difficulties the automatic pilot must be made to anticipate the motion of the ship, much in the way an experienced helmsman gives an auxiliary rudder. In practice this is accomplished by means of a feedback of rudder motion to the heading error detector, as in many commercial applications, sometimes also by adding some kind of rate of change of heading control, similar to the pitch rate component of submarine depth control systems. In effect, both these methods correspond to a "proportional plus rate control;" the first one often incorporates a non-linear character to the system [16].

With these concepts in mind we are going to try to stabilize our unstable system, first by assuming that the autopilot is just a gain G, we represent the block diagram in figure 4

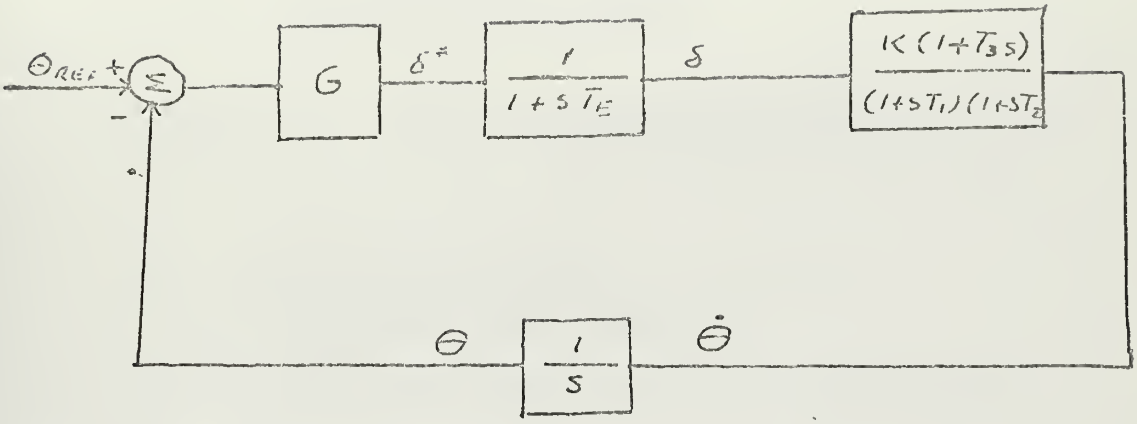


FIGURE 4

The open loop transfer function for this system is:

$$H(s) = \frac{GK(1+sT_3)}{s(1+sT_1)(1+sT_2)(1+sT_E)}$$

From experience it has been determined that T_E ranges from 1 to 2, and a good choice is 1.7 seconds, so the only parameter available to make the system stable is G.

Since there is one pole in the right hand plane, given by T_1, there is no sense in using the Bode plot to determine stability values.

1. Root-Locus Analysis

Getting the characteristic equation and arranging it in the proper form we obtain:

$$CE: \quad 1 + \frac{GK(1+sT_3)}{s(1+sT_1)(1+sT_2)(1+sT_E)}$$

$$\alpha \cdot \frac{X(s)}{Y(s)} = -1 \quad \Rightarrow \quad G\,\frac{(-.0434)(1+20s)}{s(1-269.3s)(1+9.3s)(1+1.7s)} = -1$$

$$G\,\frac{(2.04\times10^{-4})(s+0.05)}{s(s-0.0037)(s+0.59)(s+0.107)} = -1$$

Since we have four poles there are four separate loci.

There are three asymptotes due to

n # of poles = 4

n-q = 3

q # of zeros = 1

Center of asymptotes = $-\dfrac{\sum p_i - \sum z_i}{n-q} = -0.214$

Angle of asymptotes with respect to the real axis:

$$\frac{\pi + \nu\, 2\pi}{n-q} \qquad \nu = 0, 1, 2, \ldots\; n-q-1$$

$\nu = 0$ $\quad 60^\circ$

$\nu = 1$ $\quad 180^\circ$

$\nu = 2$ $\quad 300^\circ$

From a sketch made for this analysis we get the cross point at the jw axis = .025. So G at the crossing point:

$$G \geq \frac{|s|\,|s+0.59|\,|s-0.0037|\,|s+0.107|}{2.04\times10^{-4}\,|s+0.05|} = 3.2$$

2. Routh Criterion

To find a better set of numbers we refer to the Routh criterion:

$$\frac{GK(1+sT_3)}{s(1+sT_1)(1+sT_2)(1+sT_E)} = -1$$

$$s(1+sT_1)(1+sT_2)(1+sT_E) + GK(1+sT_3) = 0$$

$$s^4 + 0.692\,s^3 + 0.06\,s^2 - (2.35\times10^{-4} - 2.04\times10^{-4}G)s + 1.02\times10^{-5}G = 0$$

$$\begin{array}{llll}
s^4 & 1 & .06 & 1.02\times10^{-5}G \\
s^3 & .692 & -(2.35\times10^{-4} - 2.04\times10^{-4}G) & 0 \\
s^2 & A & 1.02\times10^{-5}G & \\
s^1 & B & 0 & \\
s^0 & 1.02\times10^{-5}G & 0 &
\end{array}$$

where

$$A = \frac{(.692)(.06) + \left(\frac{1-.868G}{4255}\right)}{.692}$$

$$B = \frac{A\left(-\frac{1-.868G}{4255}\right) - (.692)(1.02\times10^{-5}G)}{A}$$

For the stability limit in the s^1 row, B must be equal to zero so:

$$A\left(-\frac{1-.868G}{4255}\right) - (.692)(1.02\times10^{-5}G) = 0$$

after manipulation:

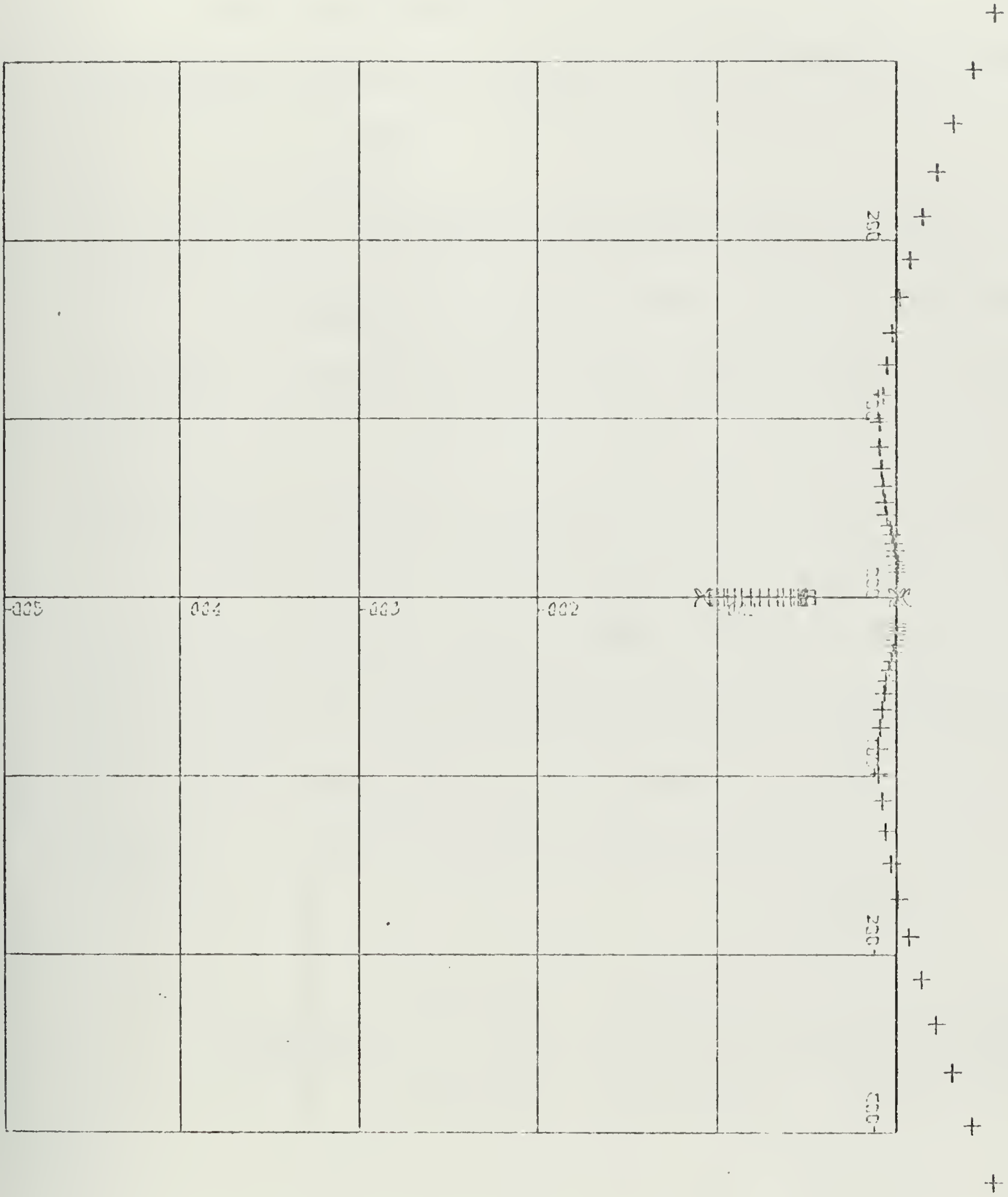
$$G^2 - 85\,G + 240 = 0$$

from where

82.0758764

$$G = \begin{matrix} 82 \\ 3 \end{matrix}$$ at the crossing points

2.924123509



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.

ROOT LOCUS OF SIMPLE AUTOPILOT
AGUAYO FIGURE 5

So we know that we have two crossing frequencies in the jw axis. In the s^2 row

$$A\,s^2 + 1.02 \times 10^{-5}\ G = 0$$

replacing the values of G, and after all the mathematics we obtain:

$$jw = \begin{matrix} j\ .0225 \\ j\ .15 \end{matrix}$$

values that agree with those approximated from the sketch.

In the figure 5, computer output of the subroutine Root Locus, we obtain the open loop characteristic of this system. As we can see the system can be considered as marginally stable due primarily to the long transient that can be predicted from the root locus graph.

Using the DSL package program we simulate the system, first the system represented by the block diagram of figure 4, and after that the same system with the concept of "proportional plus rate control," using rate of turn as feedback, as represented in figure 6

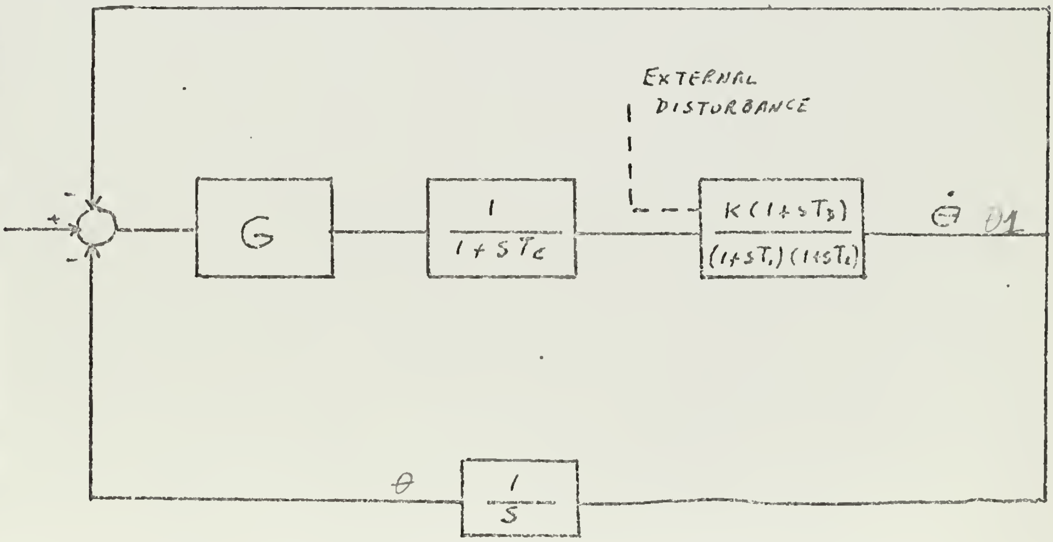


FIGURE 6

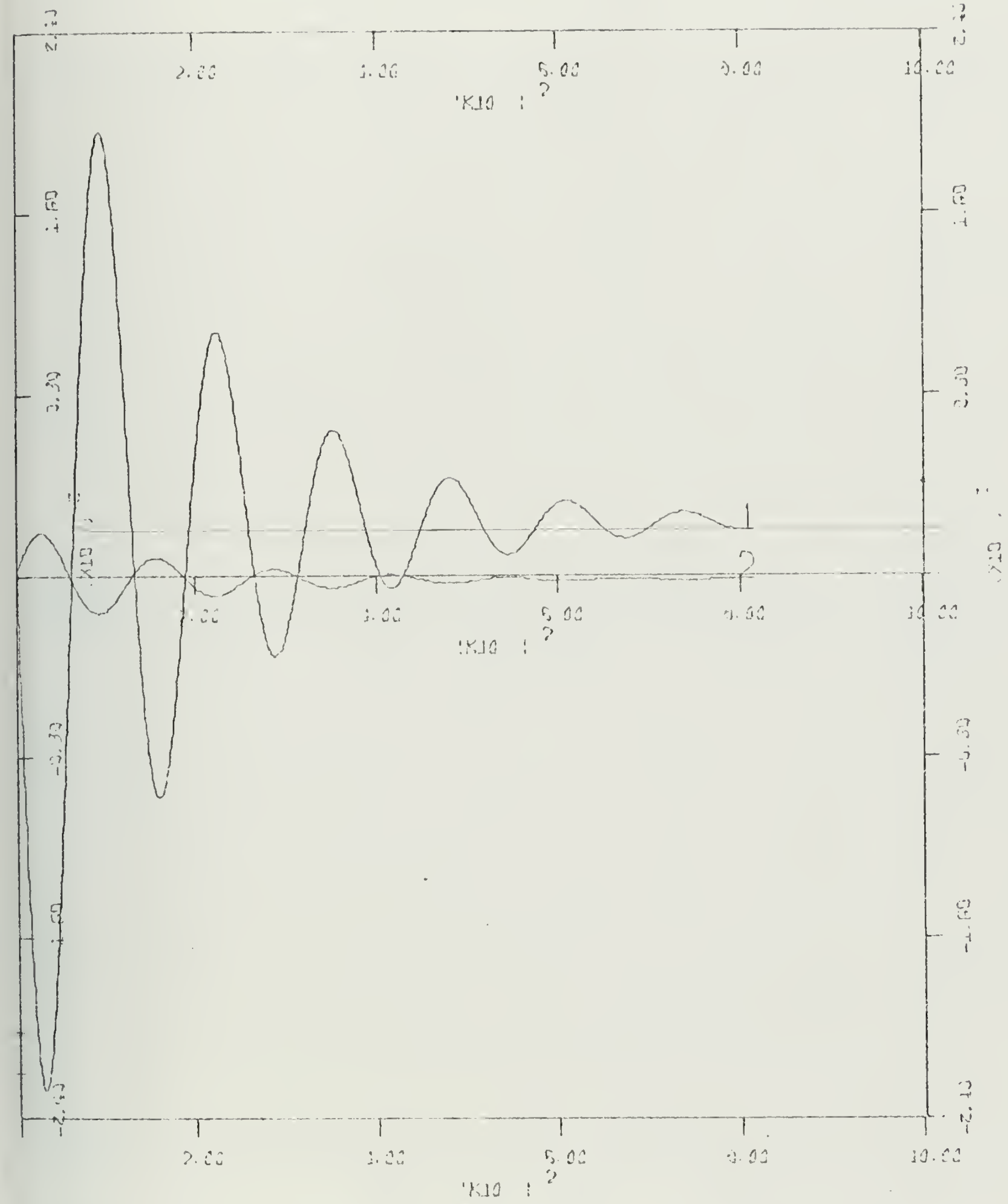
In both cases, the disturbance was simulated as a step of amplitude 1, values of G were selected between 12 and 36, which are the ones with better time constant, copy of both computer programs is given at the end of the thesis.

Figures 7-12 are computer outputs of the first condition, i.e., system of figure 4, we can see as expected, the long time required to settle down due to the small time constant of the G values, but even so we can see in figure 9 for the value of G of 24.2, comparatively a short time for reaching steady state.

Figures 13-18 are computer outputs of the second condition, i.e., system of figure 6, we get better damped results, with a significant decrement in the time to reach steady state as expected. Also in figure 15 we can see that comparatively this value of G gives us the best results. So we can state that the value of G = 24.2 is a good value to stabilize the system and perhaps the best under this conditions.

RUDDER ANGLE, THETA VS TIME K1=12

AGUAYO FIGURE 7



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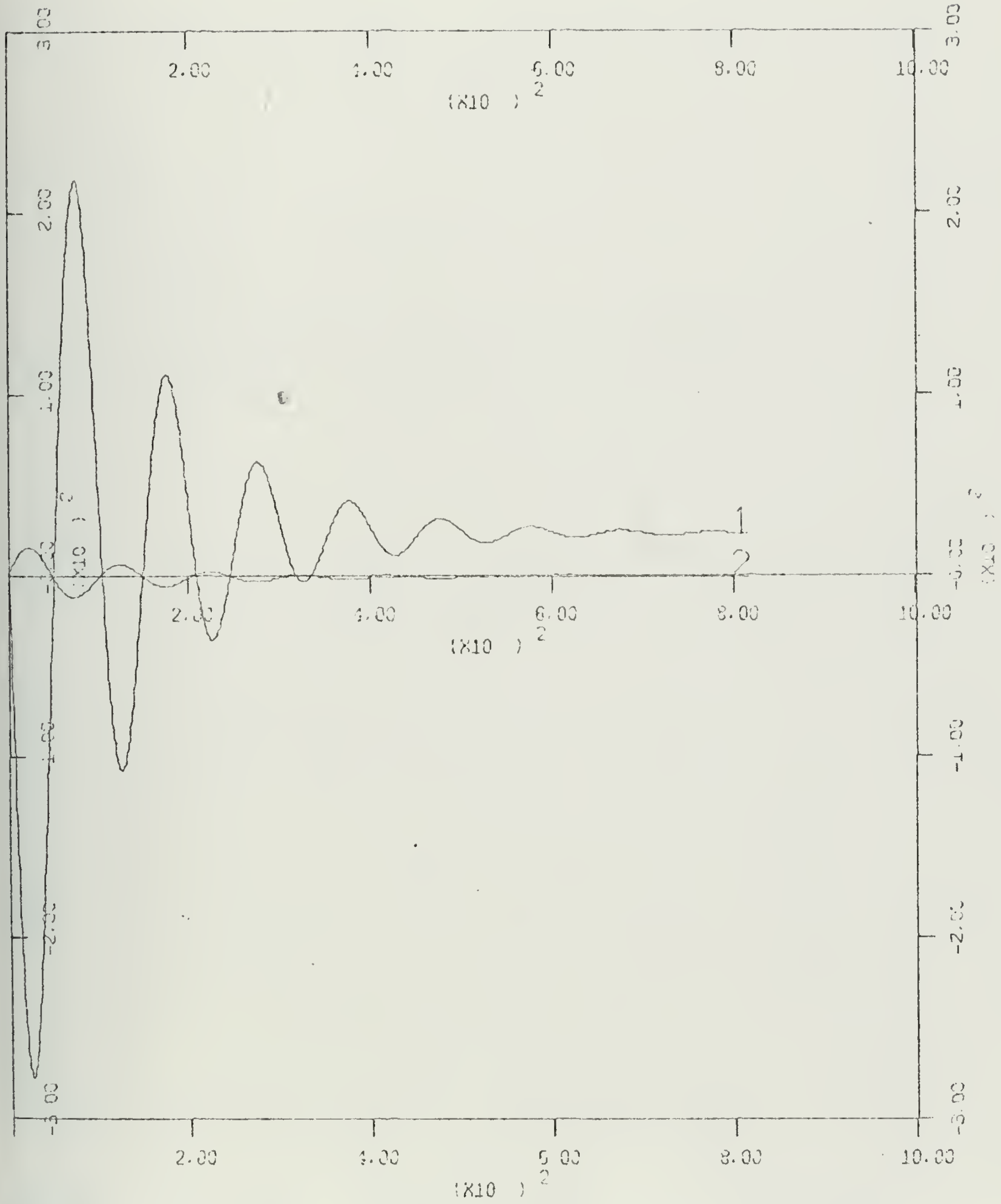
YSCALE=80.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=18

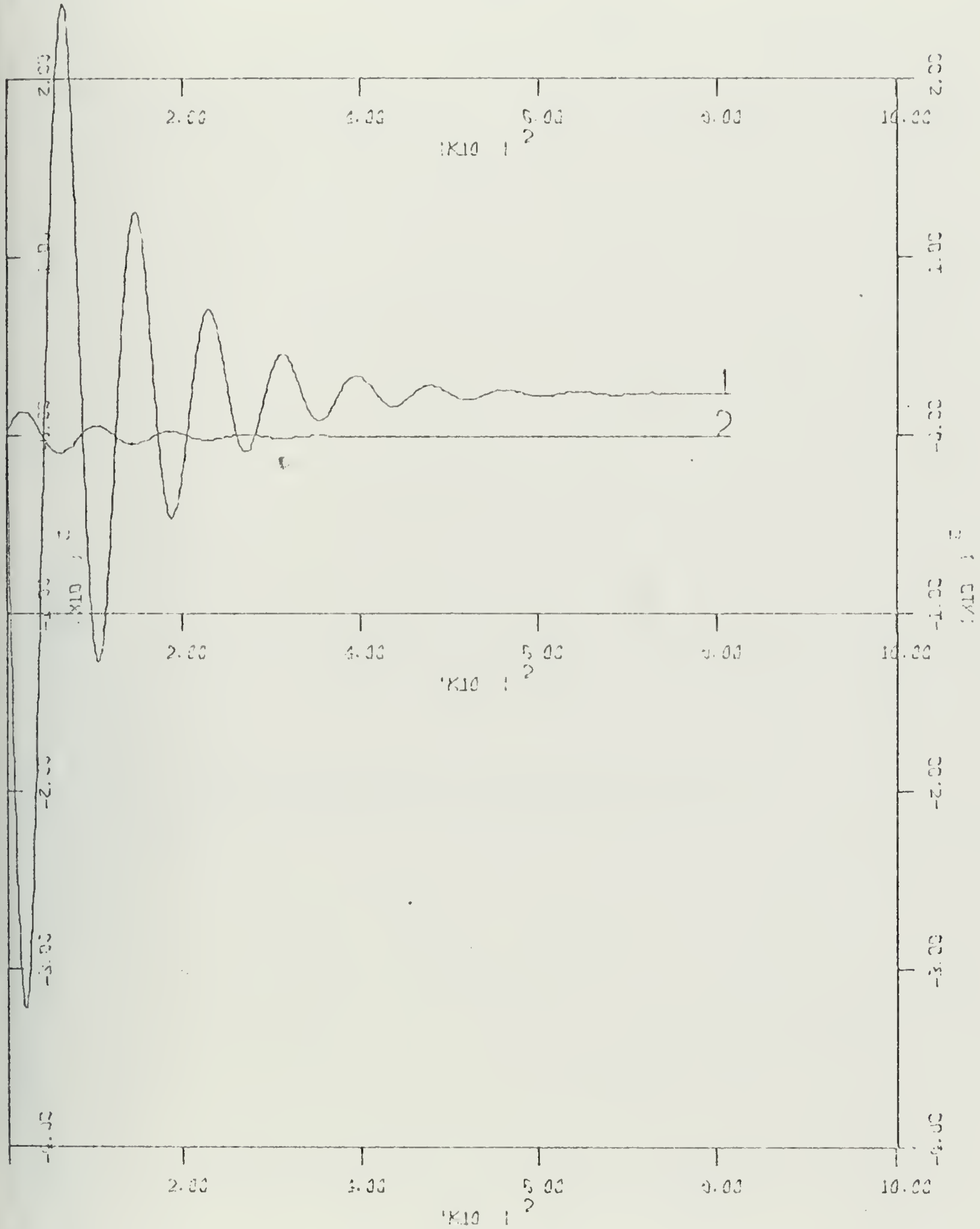
AGUAYO FIGURE 8



XSCALE=200.00 UNITS/INCH RUN NO.2
YSCALE=100.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=24.2

AGUAYO FIGURE 9

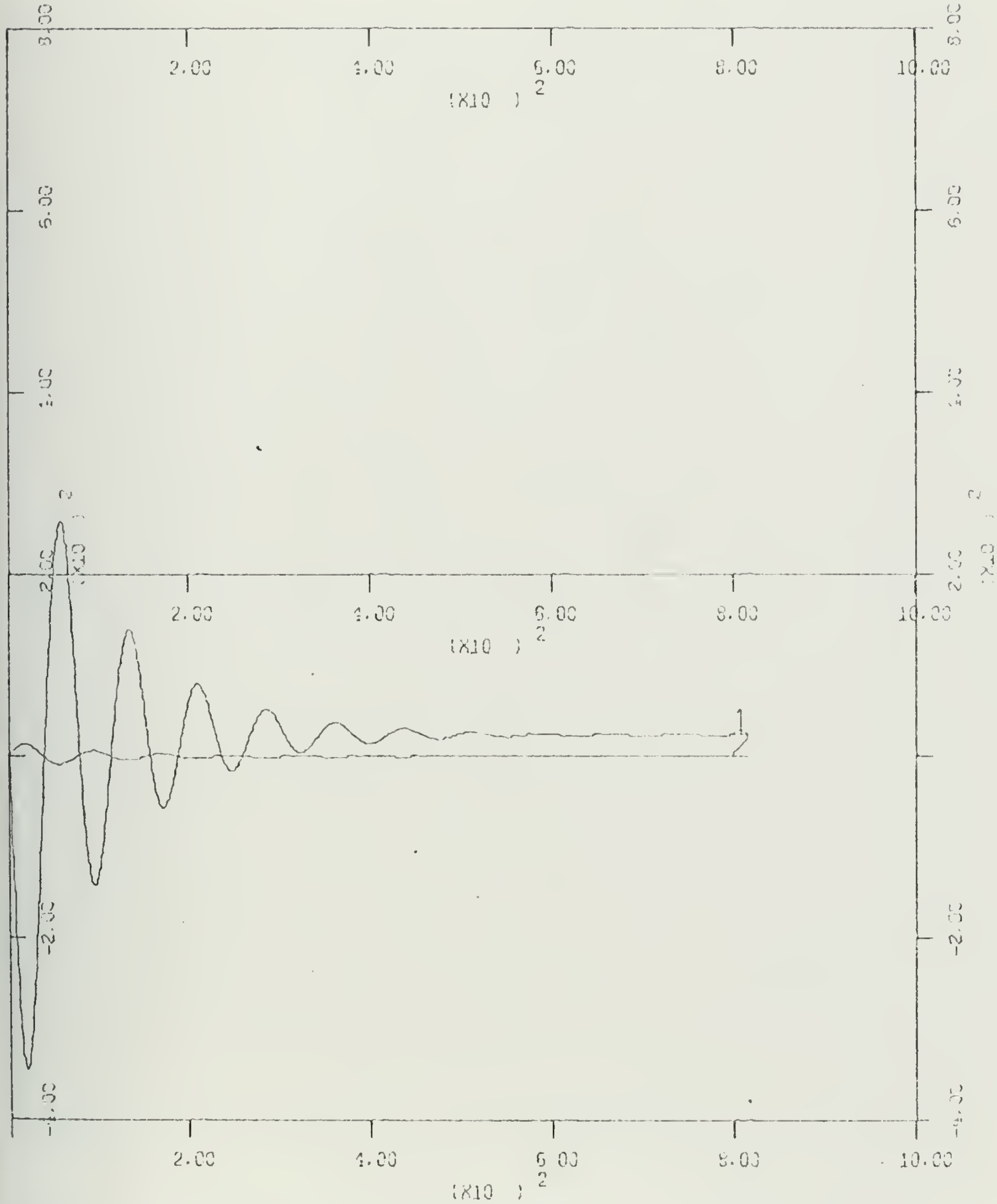


XSCALE=200.00 UNITS/INCH RUN NO.3

YSCALE=100.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=28

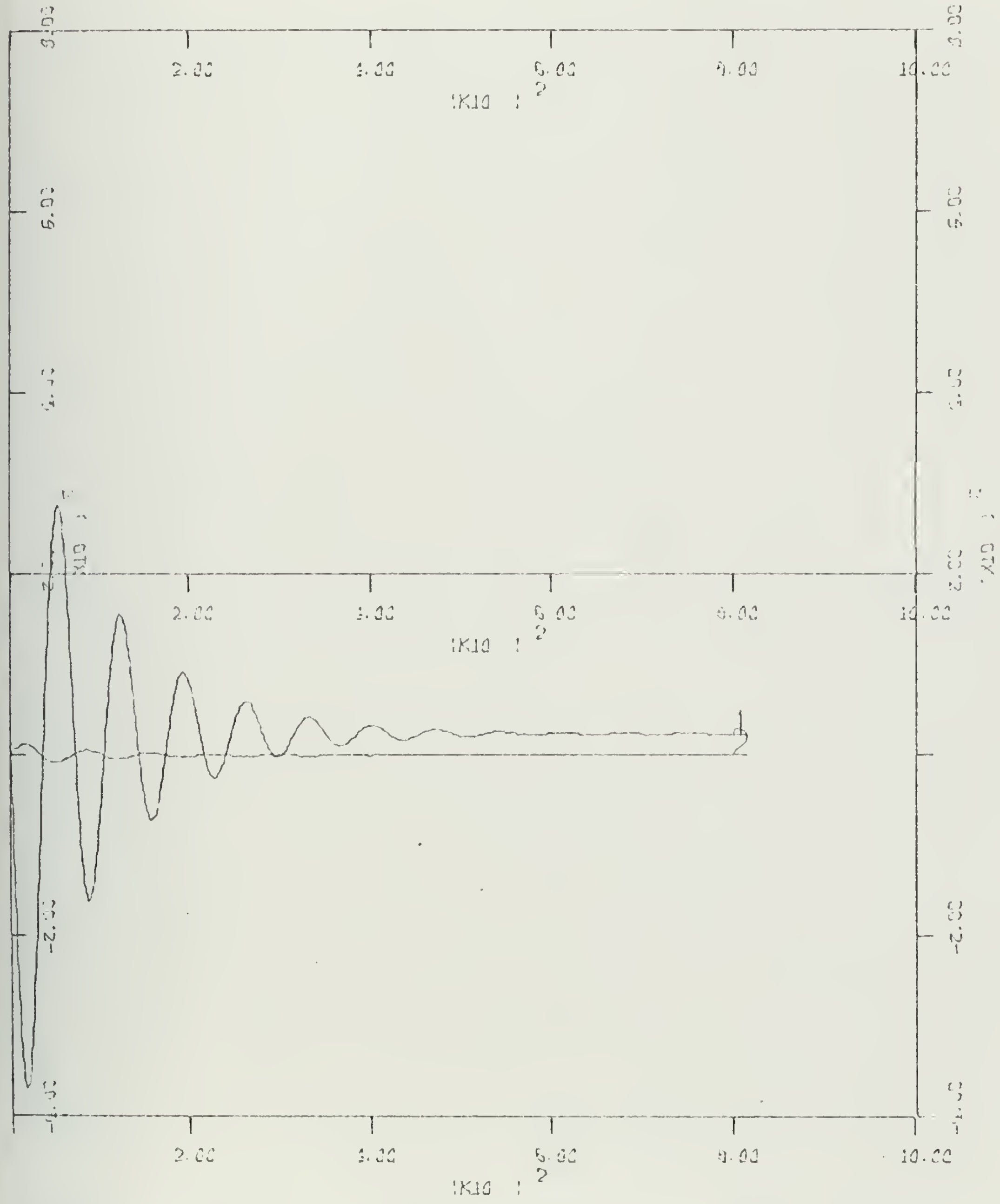
AGUAYO FIGURE 10



XSCALE=200.00 UNITS/INCH RUN NO.4
YSCALE=200.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=32

AGUAYO FIGURE 11

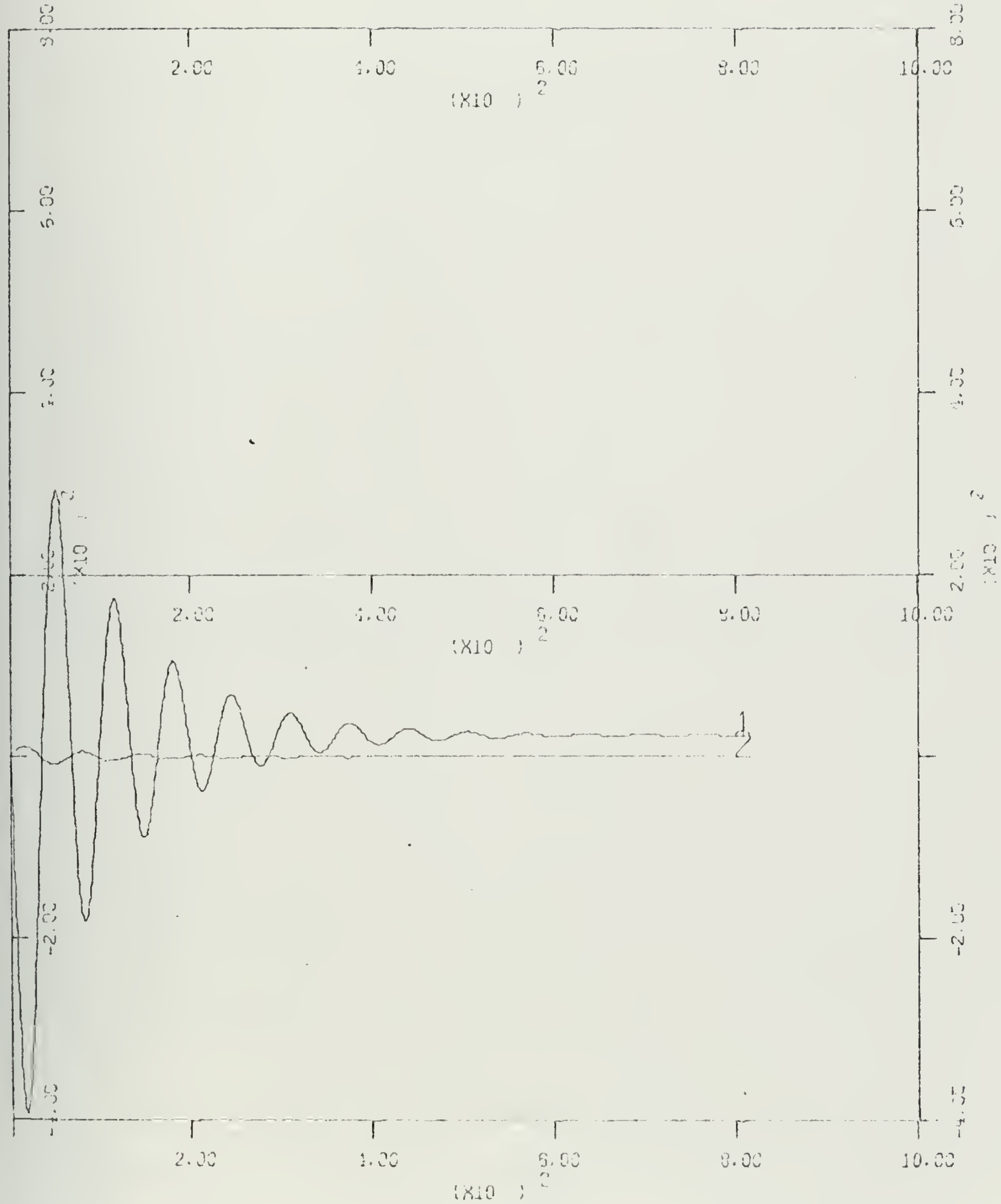


XSCALE=200.00 UNITS/INCH RUN NO.5

YSCALE=200.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=36

AGUAYO FIGURE 12

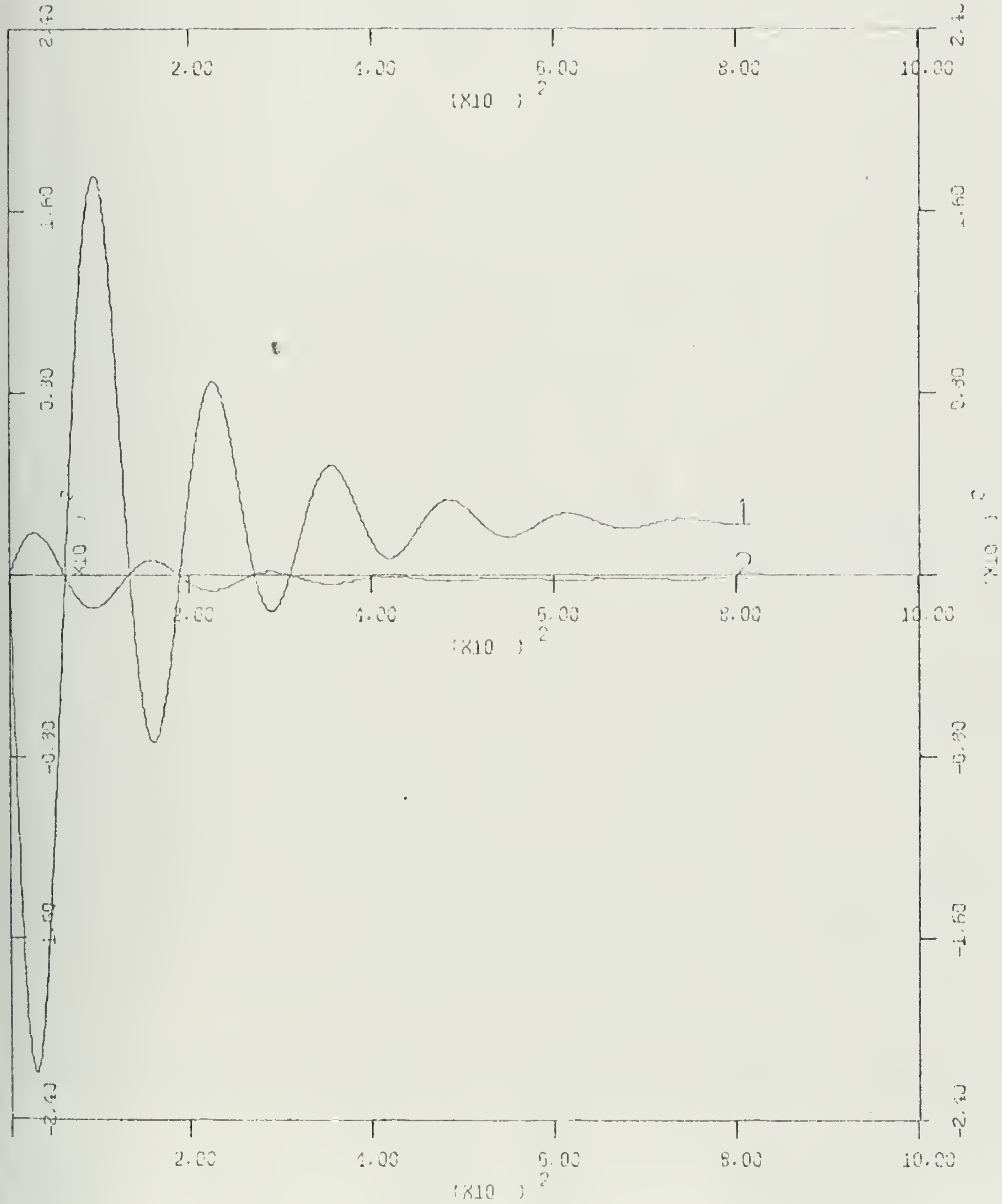


XSCALE=200.00 UNITS/INCH RUN NO. 1

YSCALE=200.00 UNITS/INCH PLOT NO. 1

RUDDER ANGLE, THETA VS TIME K1=12

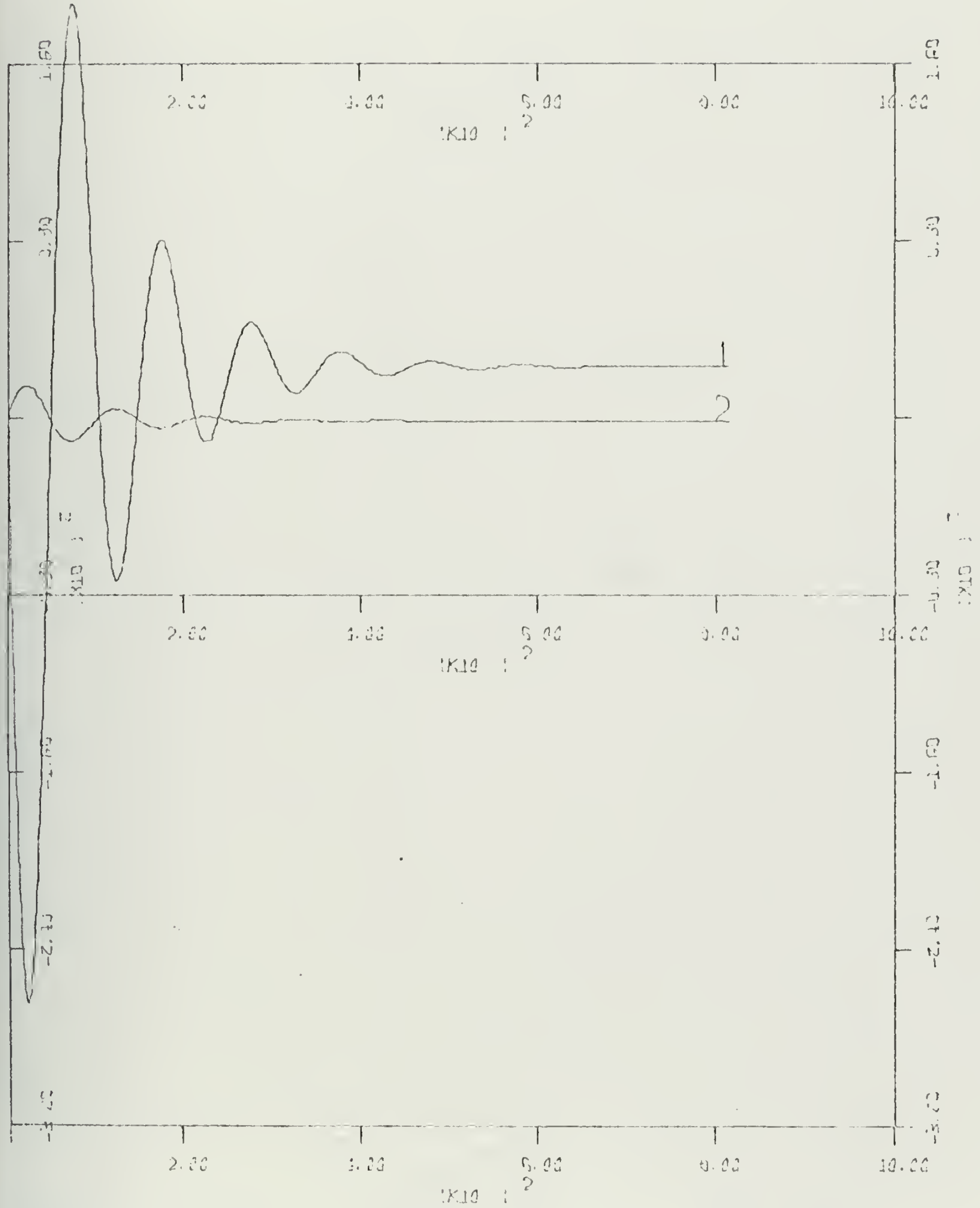
AGUAYO FIGURE 13



XSCALE=200.00 UNITS/INCH RUN NO. 1
YSCALE=80.00 UNITS/INCH PLOT NO. 1

RUDDER ANGLE, THETA VS TIME K1=18

AGUAYO FIGURE 14

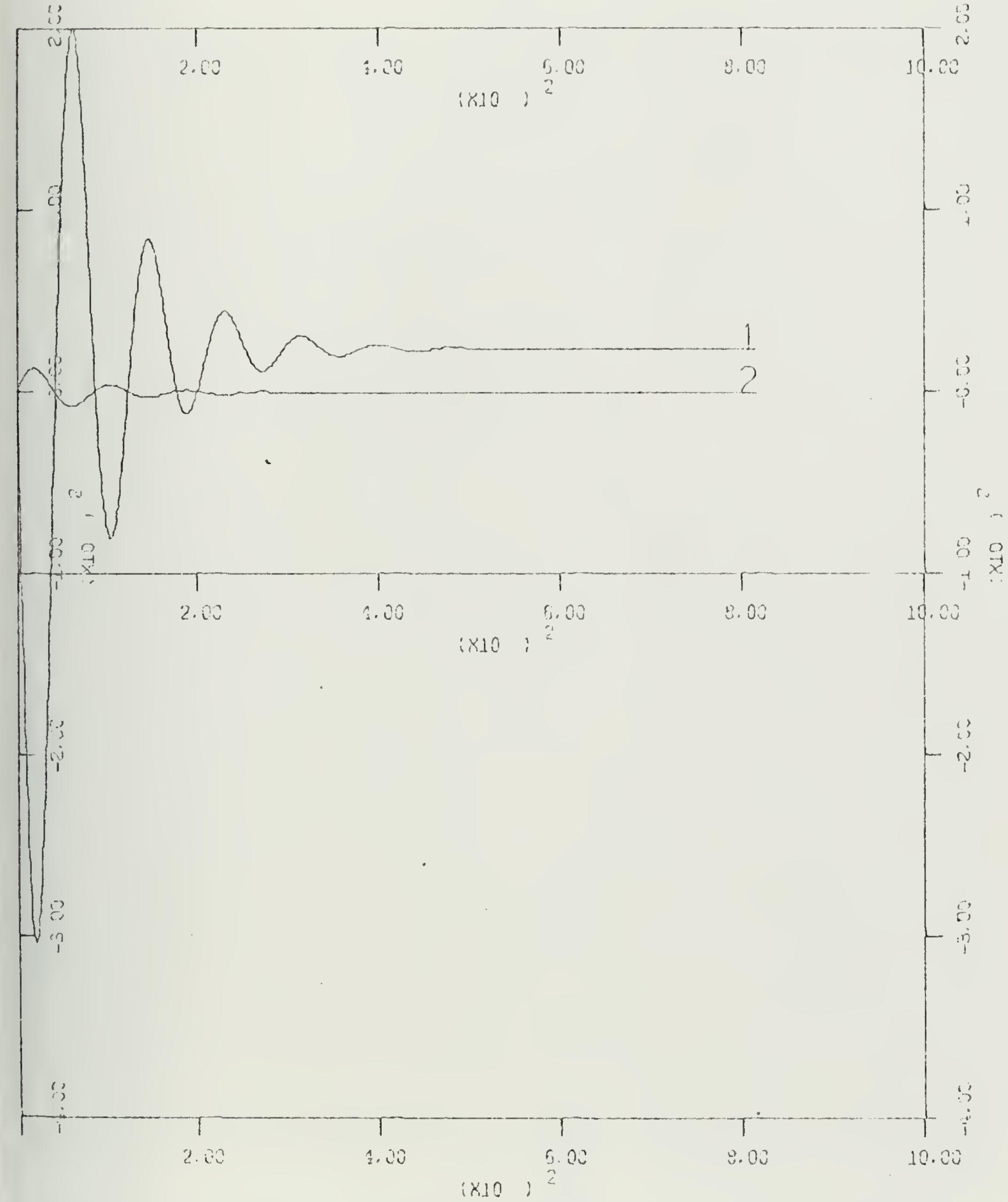


XSCALE=200.00 UNITS/INCH RUN NO.2

YSCALE=80.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=24.2

AGUAYO FIGURE 15

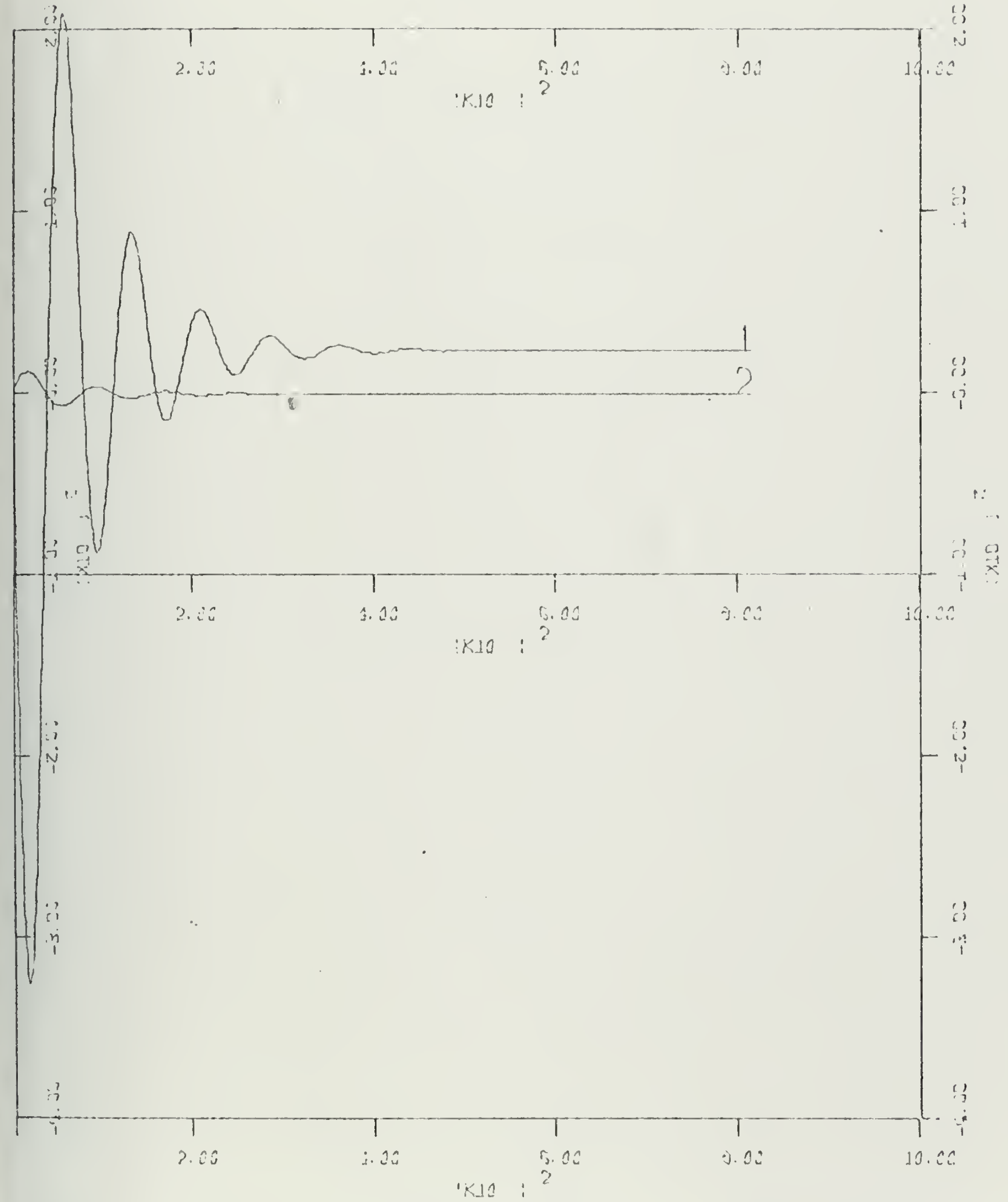


XSCALE=200.00 UNITS/INCH RUN NO.3

YSCALE=100.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=28

AGUAYO FIGURE 16

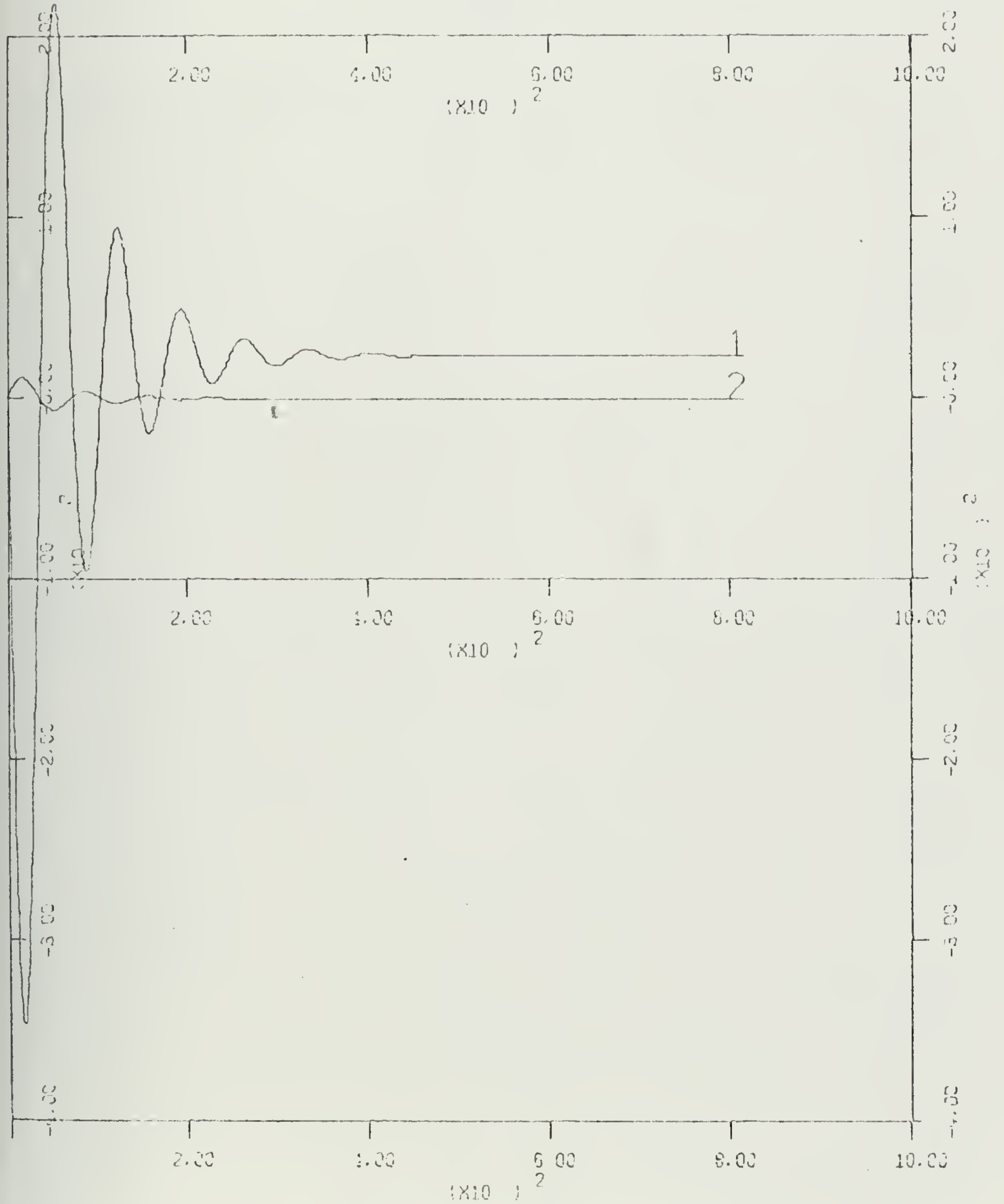


XSCALE=200.00 UNITS/INCH RUN NO.4

YSCALE=100.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=32

AGUAYO FIGURE 17

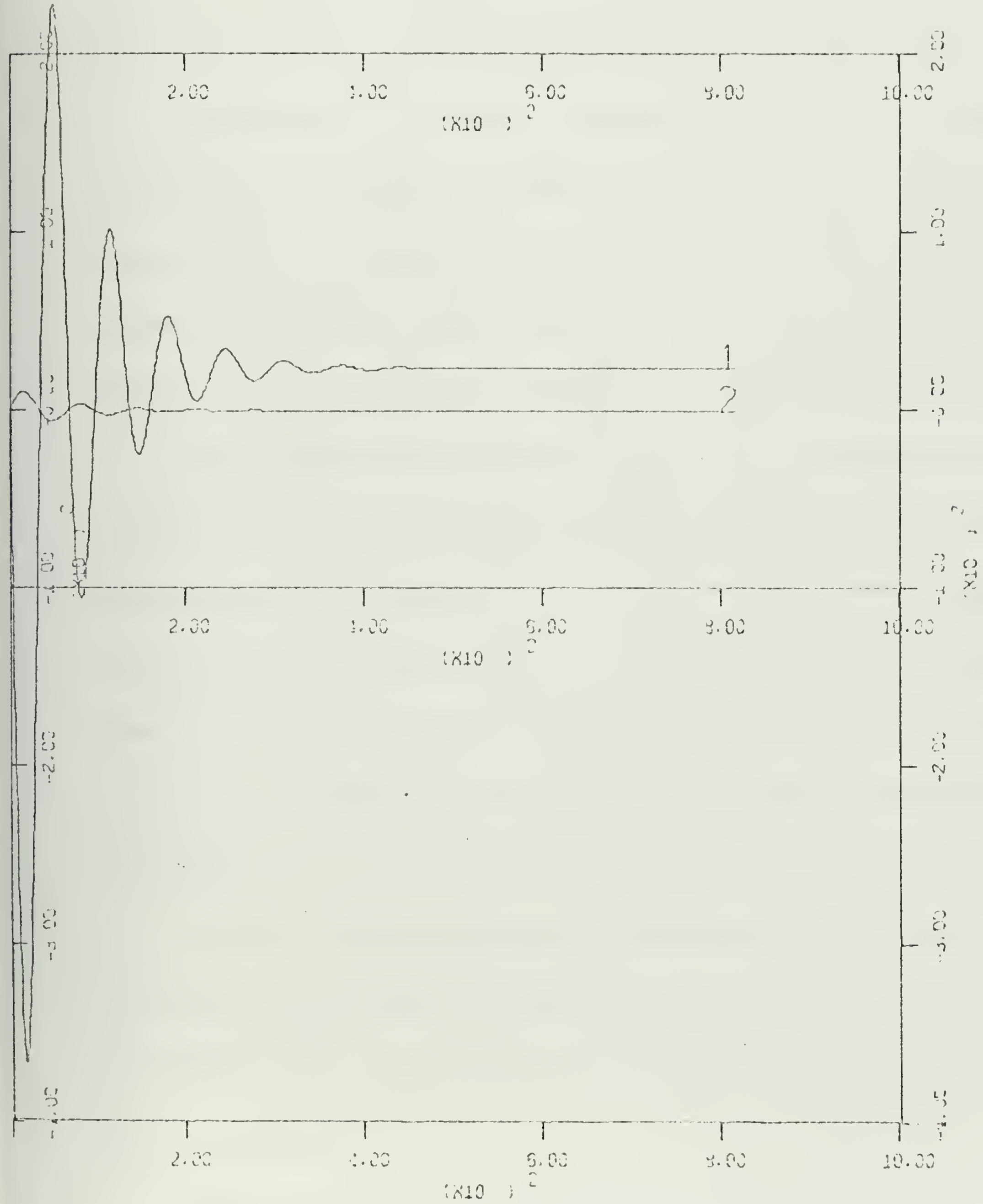


XSCALE=200.00 UNITS/INCH RUN NO.5

YSCALE=100.00 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=36

AGUAYO FIGURE 18



XSCALE=200.00 UNITS/INCH RUN NO.1

YSCALE=100.00 UNITS/INCH PLOT NO.1

IV. BASIC COURSE-KEEPING REQUIREMENTS

It is well known that the course-keeping quality and the turning quality of a ship are contradictory to each other, and that it is impossible to improve both of them without increasing rudder area [4].

The success of a rudder, designed for a particular ship, is measured by the degree to which the ship achieves a desired or anticipated course-keeping and course-changing ability. Since most ships spend most of their operating time moving ahead, it is assumed that maneuvering performance is specified only for the ahead direction.

Course-Keeping ability may be specified quantitatively in terms of the stability index, of the characteristics of the Dieudonne Spiral Maneuver (see Appendix B), or of the range of rudder angles used to maintain a straight course.[2] In reference [18], it is suggested that an attempt be made to design all ships for a stability index of zero or less, but it is recognized that this may not be practicable for all ships.

A major reason for the specification of a level of control-fixed stability for all ships is the fact that excessive controls-fixed instability leads to excessive use of the rudder to maintain a straight

---

[2] This measure of Course-Keeping ability is frequently used in maneuvering in restricted waterways or in rough seas.

course. This in turn leads to increased wear on the rudder system, decreased ship speed, or increased fuel consumption. Controls-fixed instability also leads to increased difficulty in navigation in restricted waterways and in following seas and in avoiding collision with passing ships.

A. UNDER STEADY CONDITIONS

1. Calm Water

Among the factors important for the turning motion of ships, there are transverse forces and moments acting upon ship's body itself. These may be approximately looked upon as motion in infinite fluid where image of ship is considered in case when V is not so large and the effect of waves by the ship itself with Froude Number below about 0.2 or $0.7 \sqrt{L/2d}$ [16] is negligible or when motion of ship is slow, and are the functions of V, β , $\dot{\theta}$. This will be sufficient for turning motion of ordinary ship.

The disturbances acting upon the system can be classified according to their influence on the behaviour of the system as follows:

a. Disturbances that cause deviations from the set course.

b. Disturbances which affect the steering characteristics of the ship.

Wind and waves belong to the first group, to the second class of disturbances belong the loading of the ship, the depth of the water, etc.

In considering the calm water condition we are assuming no disturbance at all, so, under these conditions we expect the ship to maintain its heading, without any action of the autopilot.

2. Steady Wind

Due to the wind pressure, the ship will be acted upon by a lift and drag which will cause the ship to drift at a drifting angle. By the drifting, the hull together with the rudder will create a certain hydrodynamic lift, drag and moment until the windward component of the hydrodynamic force balances with the wind drag. At this condition, the total summation of forces including ship's thrust is zero. However, the summation of the moment including moment due to the rudder at maximum helm angle will not necessarily be zero.

If the summation of the moment is not zero, and is in a direction to increase, the ship will have a tendency to turn windward. If the moment is in an inverse direction the ship will turn leeward. In both cases, the ship is supposed to be uncontrollable. If the summation of the moment is zero within the range where rudder angle does not exceed 30 degrees, the ship can keep its heading so that it is supposed to be controllable.

B. ACCURACY NEED FOR COURSE-KEEPING

1. Loop Gain

The most important parameter to be considered in considering automatic control is the Loop Gain, and its value depends directly on the transient response of the system.

For linear systems, the most commonly used correlation between frequency response and transient response is that correlation which exists between the height of the resonance peak M_{pw} and the height of the peak overshoot of the step response M_p for a second-order system. A curve relating these is easily calculated [20]. Then, for a known second-order frequency response, the curve is entered with M_{pw} and the transient peak overshoot M_{pt} is predicted exactly. When the system is known to be third-, fourth-, or higher-order, there is no such readily available correlation, but the second-order correlation may be used as an estimate. This gives a very accurate estimate if the higher-order response is dominated by one pair of complex roots, a less accurate estimate if dominance is not assured.

We know that in order to make a system stable within some degree of accuracy we need to have complex roots, and a certain value of gain. In our study where we are operating with a giant of 200,000 Tons., we can afford to have a certain degree of inaccuracy, i.e., 1 to 2 degrees of heading error, without consequences, so we can go, if required, to have real roots governing our system.

2. Loop Type Number

Control systems, in general, are required to have certain operating characteristics which are determined quantitatively by the specific control problem, but which may be listed qualitatively the ones we are interested in as follows:

a. The system must be accurate in steady state.

b. The system must be stable.

c. The system must regulate against disturbances.

Each problem on feedback control has a different set of performance requirements that must be satisfied, but the requirement that is common to virtually all problems is a need for accuracy. What is meant by accuracy depends on the specific physical application, and no convenient broad definition is available, but the scope of accuracy requirements is readily illustrated. The class of control system we are interested in is the class of positioning system or servomechanisms. These systems are designed to change the output quantity as commanded by an input signal, and in addition are required to act as regulators in the presence of output disturbances. The primary consideration is usually that of keeping the error (difference between commanded output and actual output) less than a specified amount when the system is in steady state with no load disturbances. If static load disturbances are anticipated a separate specification for steady error is usually given, and for a suddenly applied disturbance a maximum instantaneous error may be specified.

For positioning systems subject to command input signals, there are also specifications as to the permissible nature of the transient response, but these specifications usually refer to the permissible time duration of the transient and to the permissible

nature of any oscillations during the transient period. They seldom refer directly to the accuracy of the system, but the constraints which they place on the system design may make it very difficult to satisfy the accuracy specifications.

Systems classified as positioning systems may be subjected to various types of input commands. These may be well defined and representable as simple mathematical functions or they may be rather complex functions of time. For well defined inputs the system usually (not always) reaches a finite steady state condition so that the accuracy of the system is readily evaluated. For more complex inputs the system may not reach a clearly defined steady state condition, so that the accuracy must be evaluated in terms of bounds and a numerical value for "steady state error" may not exist.

In this study emphasis is placed on system analysis and design for cases where the accuracy problem is defined in terms of deterministic input signals.

V. DESIGN OF COMPENSATION

Having been able to obtain the best value for the gain of the autopilot to stabilize the unstable model, we see that the transient is still too large and has overshoots (due primarily to the hydrodynamic coefficients of the ship, which are given, as we may recall by the steering quality indices).

With the concepts of chapter IV we are going to approach the design of the compensation using the Root-Locus method instead of the Bode Plot, since having a pole in the right hand plane the latter is hard to use.

A. RATE GYRO COMPENSATOR

Because of the shape of the Root Locus diagram we need to improve the transient response. By using a Rate Gyro we introduce an additional zero at 1/k, and this relocates the roots on the Root Locus plot at a different gain level. Rate feedback is a very common means of increasing equivalent fiscous damping and of thus improving system transient response. Figures 19 and 20 are a block diagram representation of heading feedback, the original circuit and the equivalent respectively.

The new characteristic equation is

$$1 + \frac{GK(1+sT_3)(1+ks)}{s(1+sT_1)(1+sT_2)(1+sT_E)} = 0$$

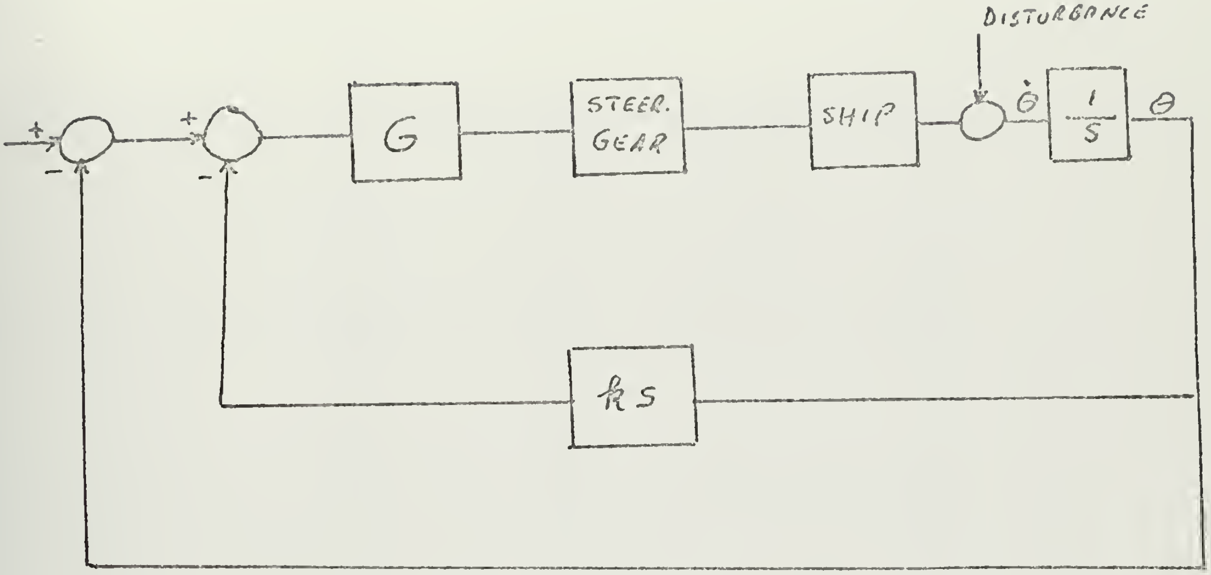


FIGURE 19

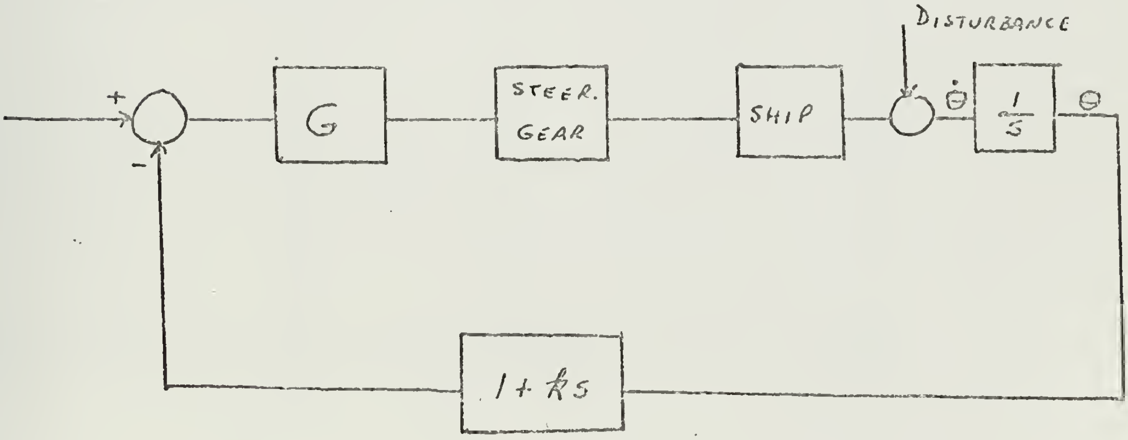
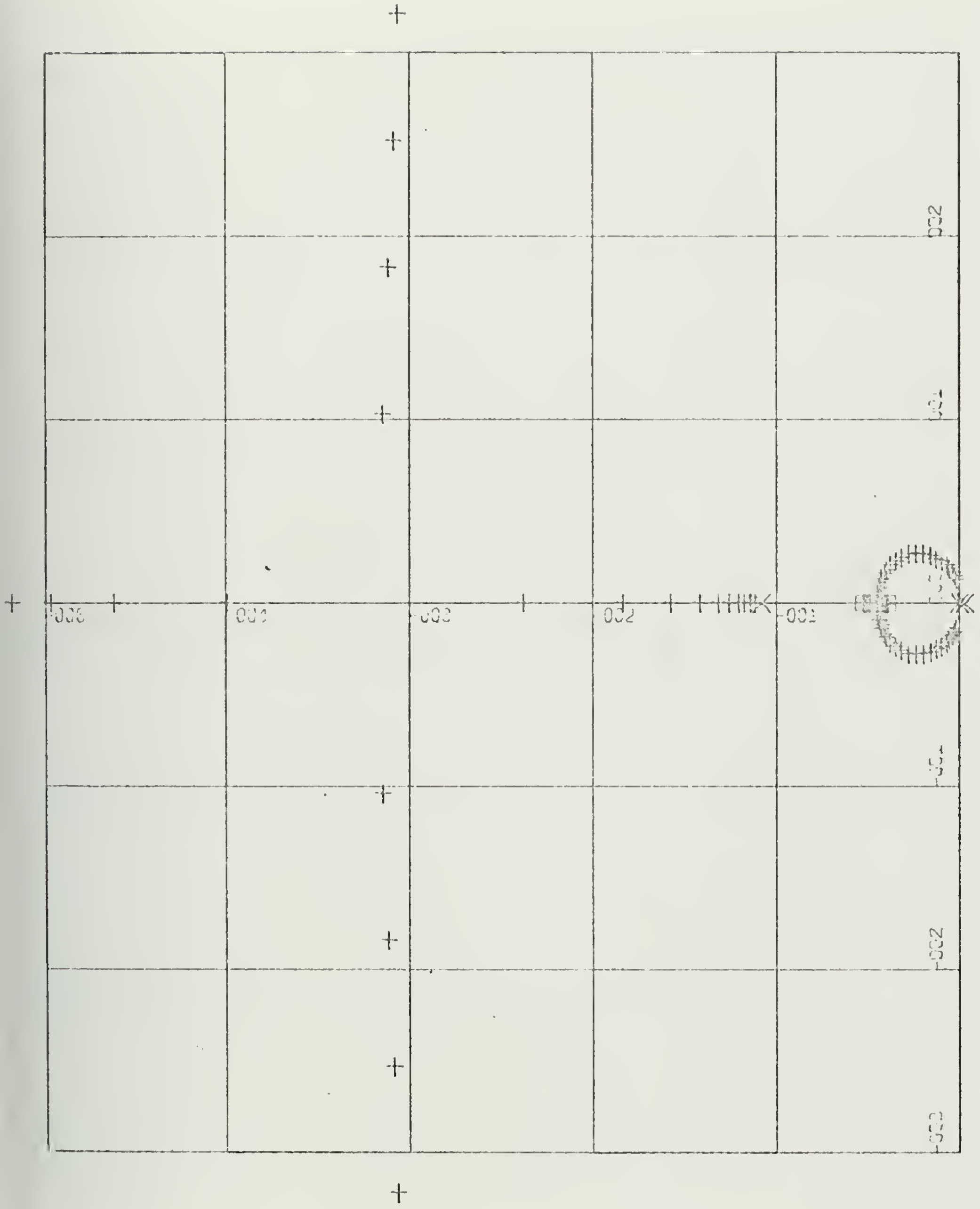


FIGURE 20

[illegible]



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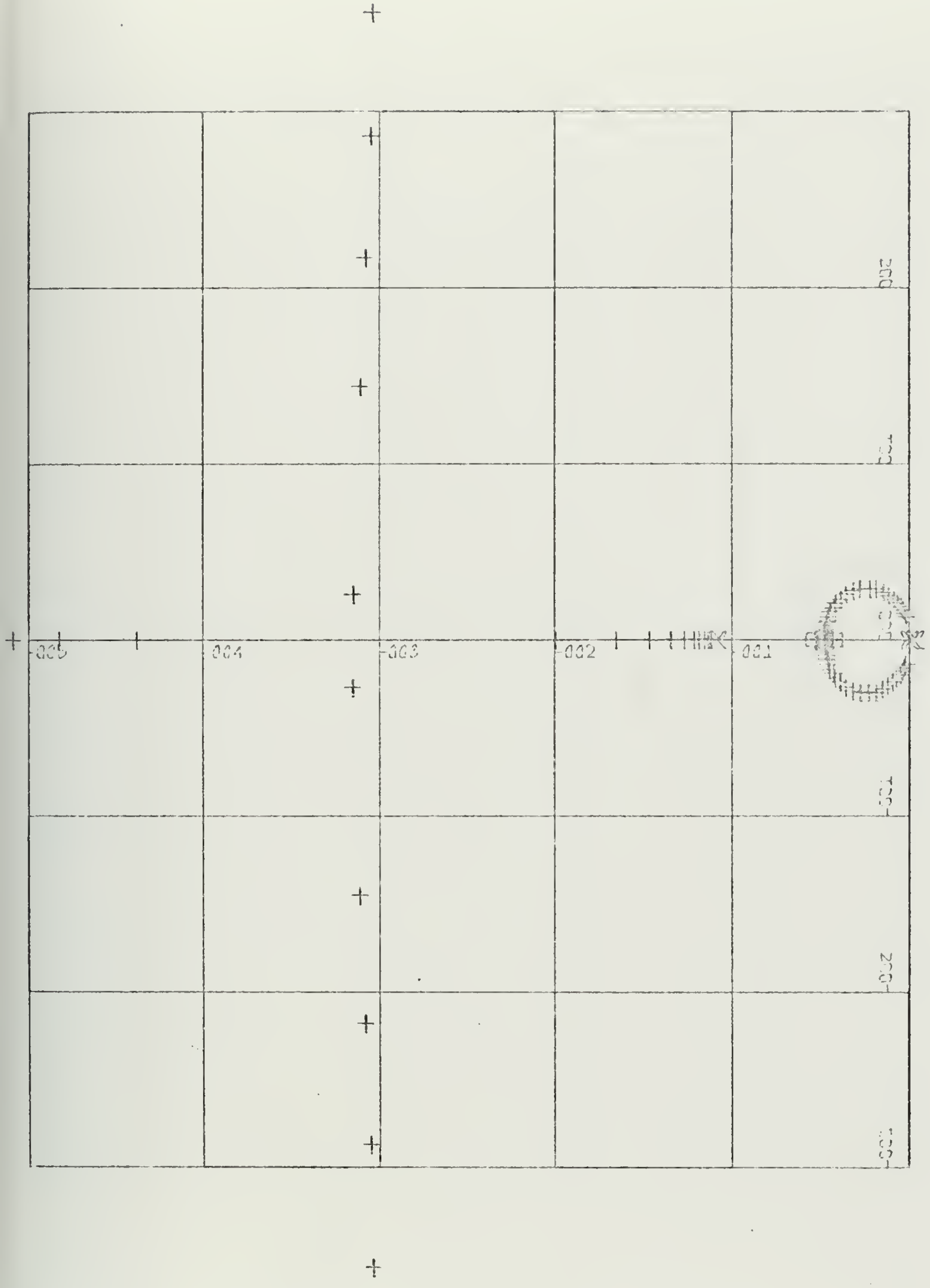
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 1 COMPENSATED
AGUAYO FIGURE 21



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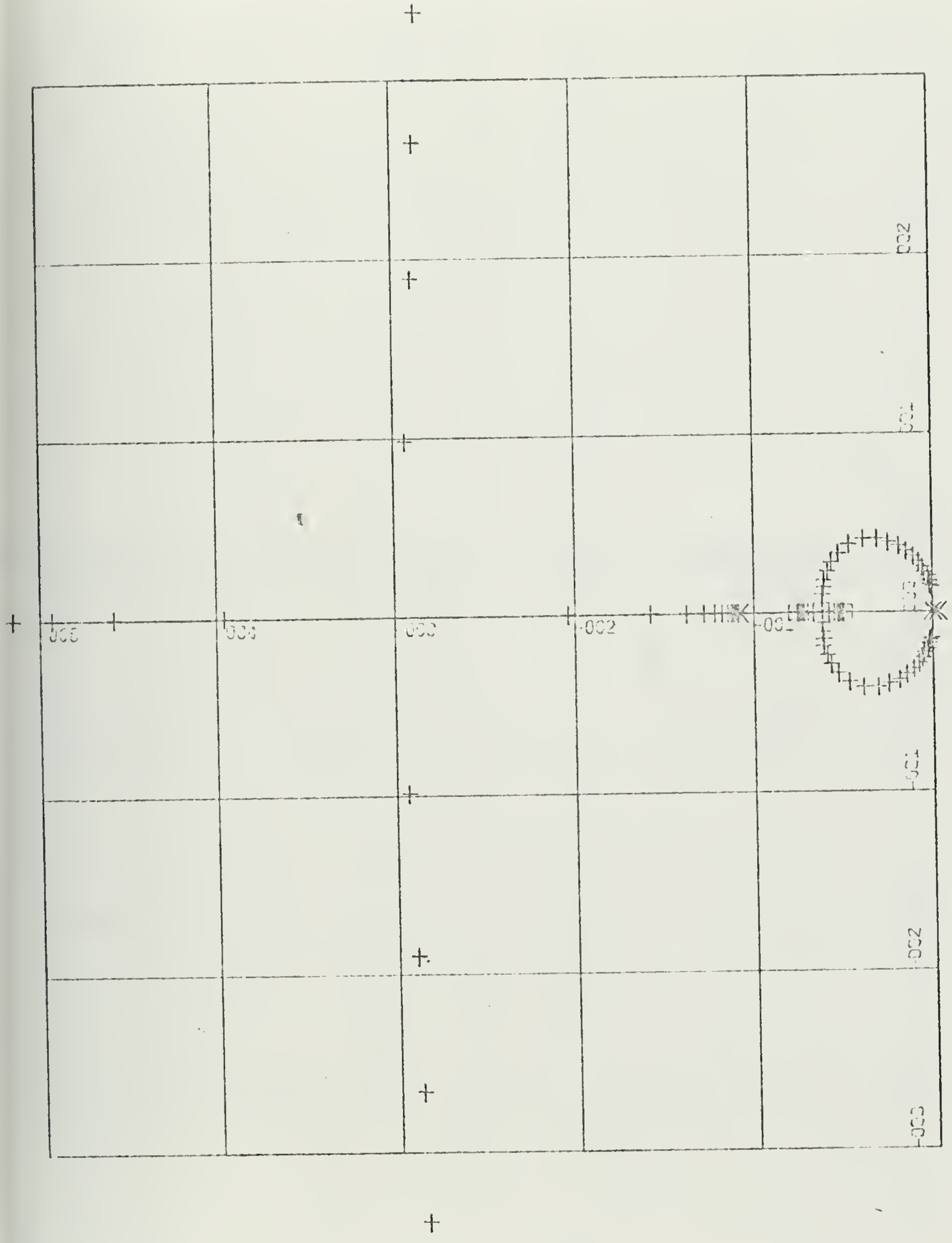
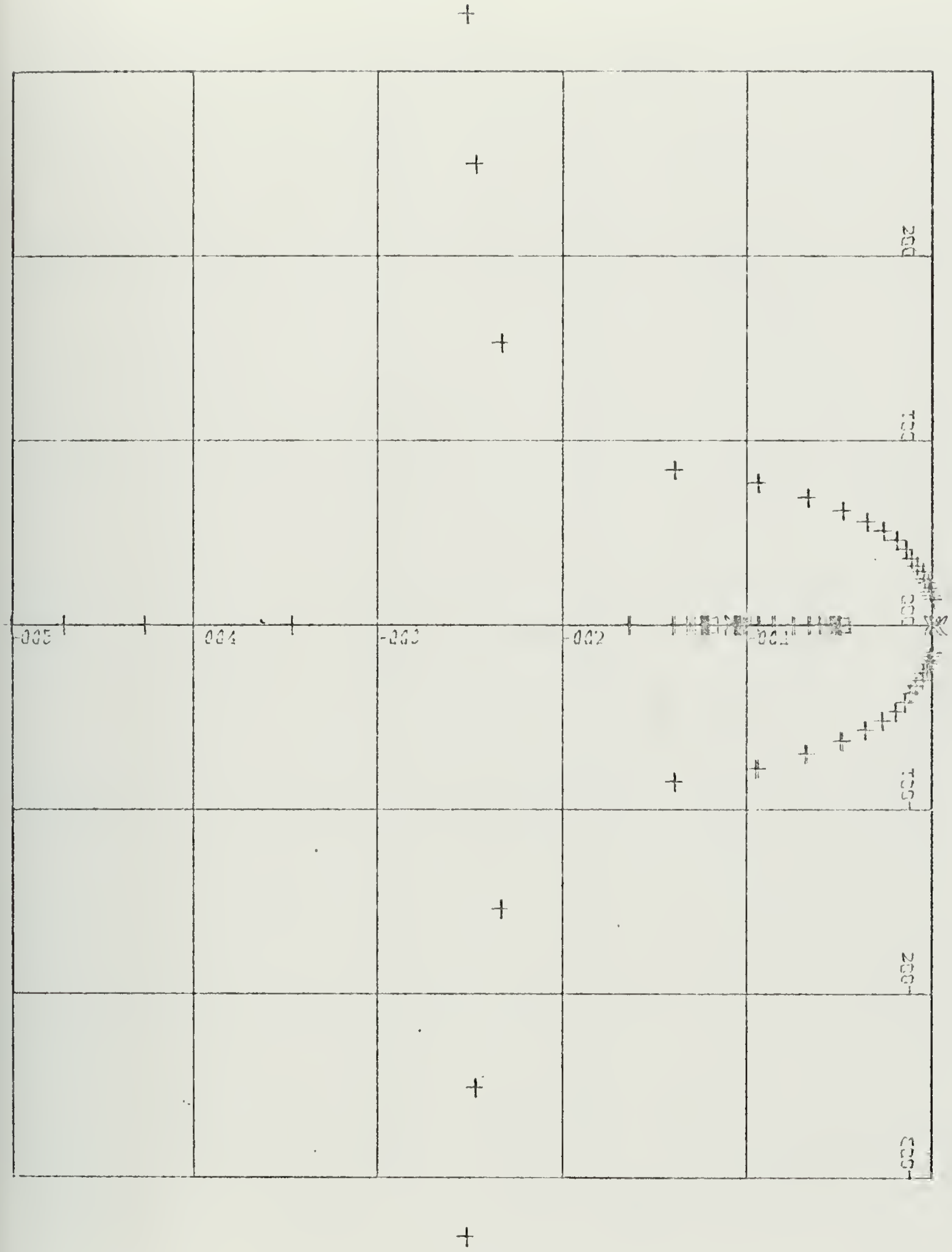
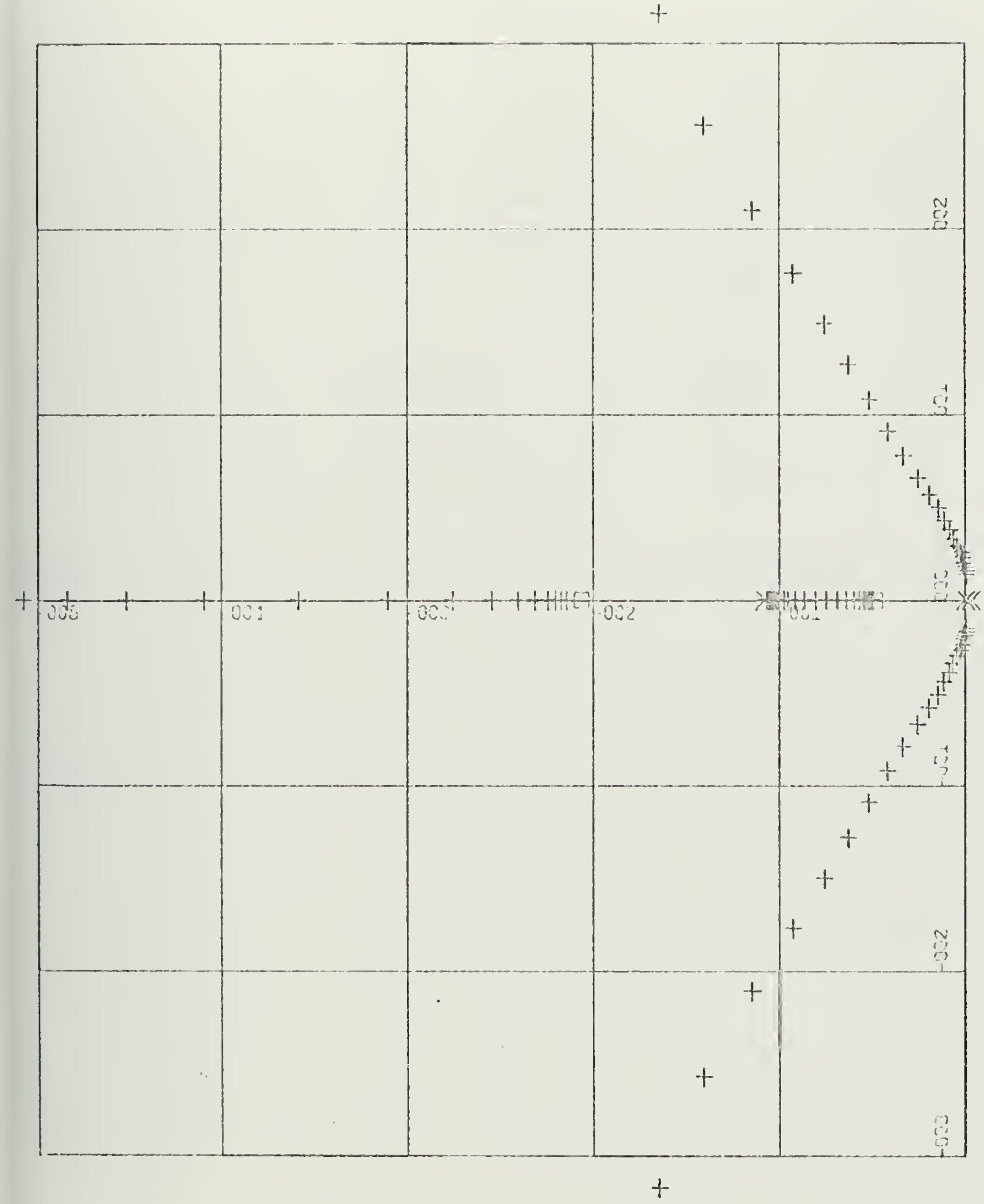
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 2 COMPENSATED
AGUAYO FIGURE 22



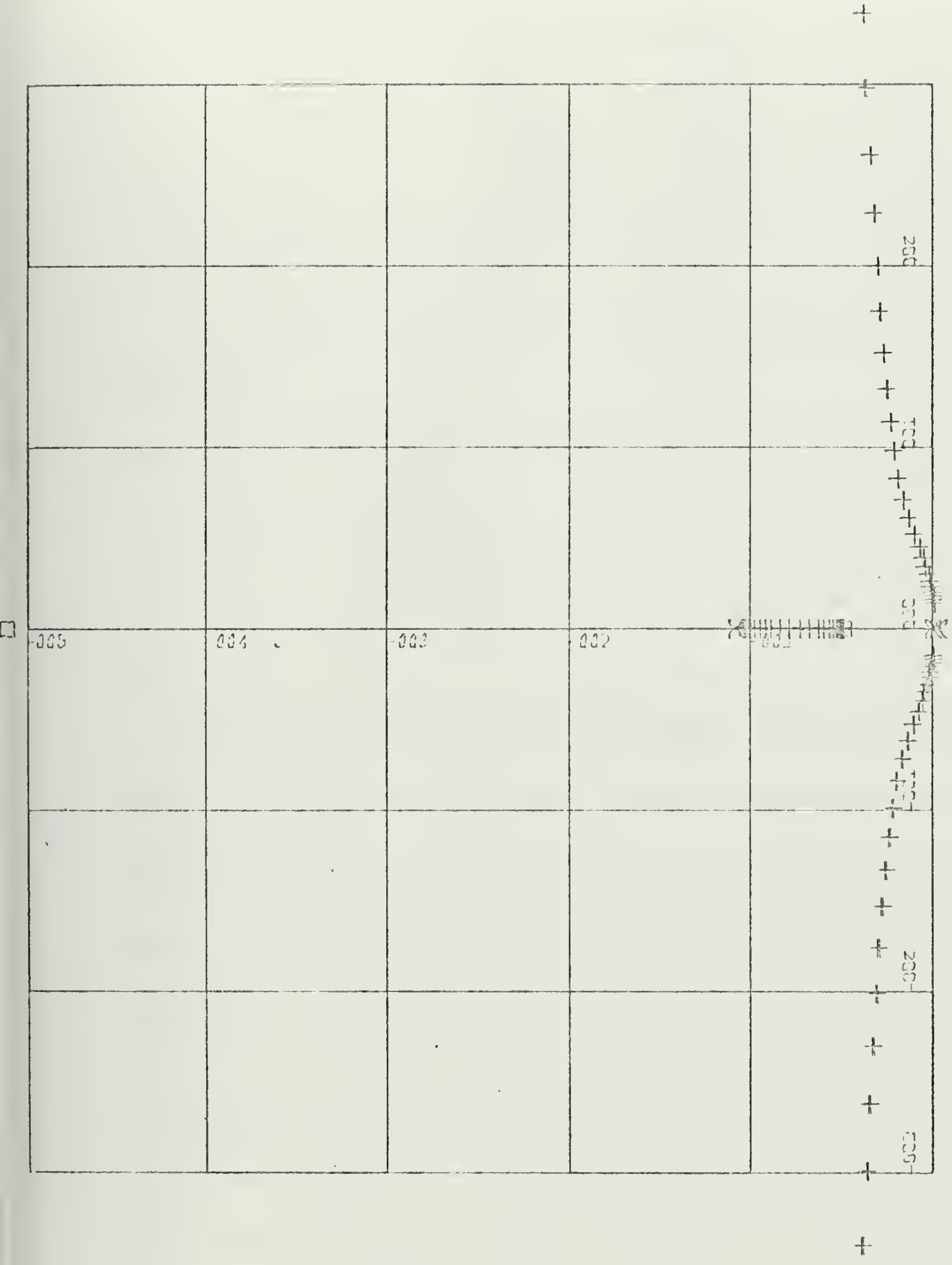
X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 3 COMPENSATED
AGUAYO FIGURE 23



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 4 COMPENSATED
AGUAYO FIGURE 24



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 5 COMPENSATED
AGUAYO FIGURE 25



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS GYRO 6 COMPENSATED
AGUAYO FIGURE 26

by selecting six values of k as:

k	$1/k$
25	.04
22.2	.045
13.35	.075
8.55	.117
5.	.2
2.	.5

we obtain the 4th order polynomials to use in the Root-Locus analysis:

$$s^4 + .692\, s^3 + (.06 + 5.07 \times 10^{-3} G) s^2 + (-2.35 \times 10^{-4} + 4.61 \times 10^{-4} G) s + 1.02 \times 10^{-5} G = 0$$

4.53×10^{-3}	4.34×10^{-4}
2.74×10^{-3}	3.43×10^{-4}
1.74×10^{-3}	2.94×10^{-4}
1.01×10^{-3}	2.58×10^{-4}
4.06×10^{-4}	2.28×10^{-4}

Figures 21-26 are computer outputs of the subroutine Root-Locus. They give the different system behaviour for the values of k selected. As we can see from figures 24-26 in order to have a good time constant we need a large value of G, and from figures 21-23 we can select very small values of G, which will give us real roots.

B. LEAD TYPE FILTER COMPENSATOR

Another type of compensation uses a filter with transfer function of the form:

$$\boxed{k} \frac{s + z}{s + p} \qquad \frac{p}{z}$$

having high pass characteristics. We are going to relocate, also, the roots on the Root-Locus diagram. This filter is just a cascaded

transfer function in the direct path between input and output, on our system. We are going to introduce one additional pole and zero.

Figure 27 shows the block diagram with the filter in the system

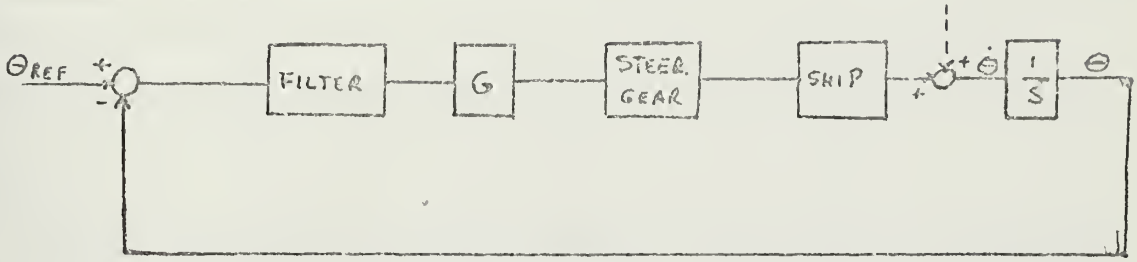


FIGURE 27

The characteristic equation is:

$$1 + \frac{G K k (1+ST_3)(S+z)}{S(S+p)(1+ST_1)(1+ST_2)(1+ST_E)} = 0$$

by selecting the values of z and p as:

z	p	z/p	$1/p$
.04	.4	.1	2.5
.045	.45	.1	2.22
.075	.75	.1	1.33
.117	1.17	.1	.855
.2	2.	.1	.5
.5	5.	.1	.2

we obtain the 5th order polynomials to use in the Root-Locus plot:

$$\begin{array}{lll} S^5 + 1.085\, S^4 & + .335\, S^3 & + (2.39\times10^{-2} + 2.01\times10^{-3} G)\, S^2 \\ \quad 1.138 & \quad .370 & \quad 2.7\times10^{-2} \\ \quad 1.438 & \quad .578 & \quad 4.57\times10^{-2} \\ \quad 1.856 & \quad .867 & \quad 7.05\times10^{-2} \\ \quad 2.680 & \quad 1.438 & \quad 12.\times10^{-2} \\ \quad 5.683 & \quad 3.515 & \quad 30.\times10^{-2} \end{array}$$

$$\begin{array}{lll} + (-9.34\times10^{-5} & + 1.82\times10^{-4} G)\, S & + 4.05\times10^{-6} G = 0 \\ \quad -10.5\times10^{-5} & \quad 1.92\times10^{-4} & \quad 4.56\times10^{-6} \\ \quad -17.5\times10^{-5} & \quad 2.54\times10^{-4} & \quad 7.62\times10^{-6} \\ \quad -27.3\times10^{-5} & \quad 3.39\times10^{-4} & \quad 11.89\times10^{-6} \\ \quad -46.7\times10^{-5} & \quad 5.06\times10^{-4} & \quad 20.28\times10^{-6} \\ \quad -117.2\times10^{-5} & \quad 11.1\times10^{-4} & \quad 50.87\times10^{-6} \end{array}$$

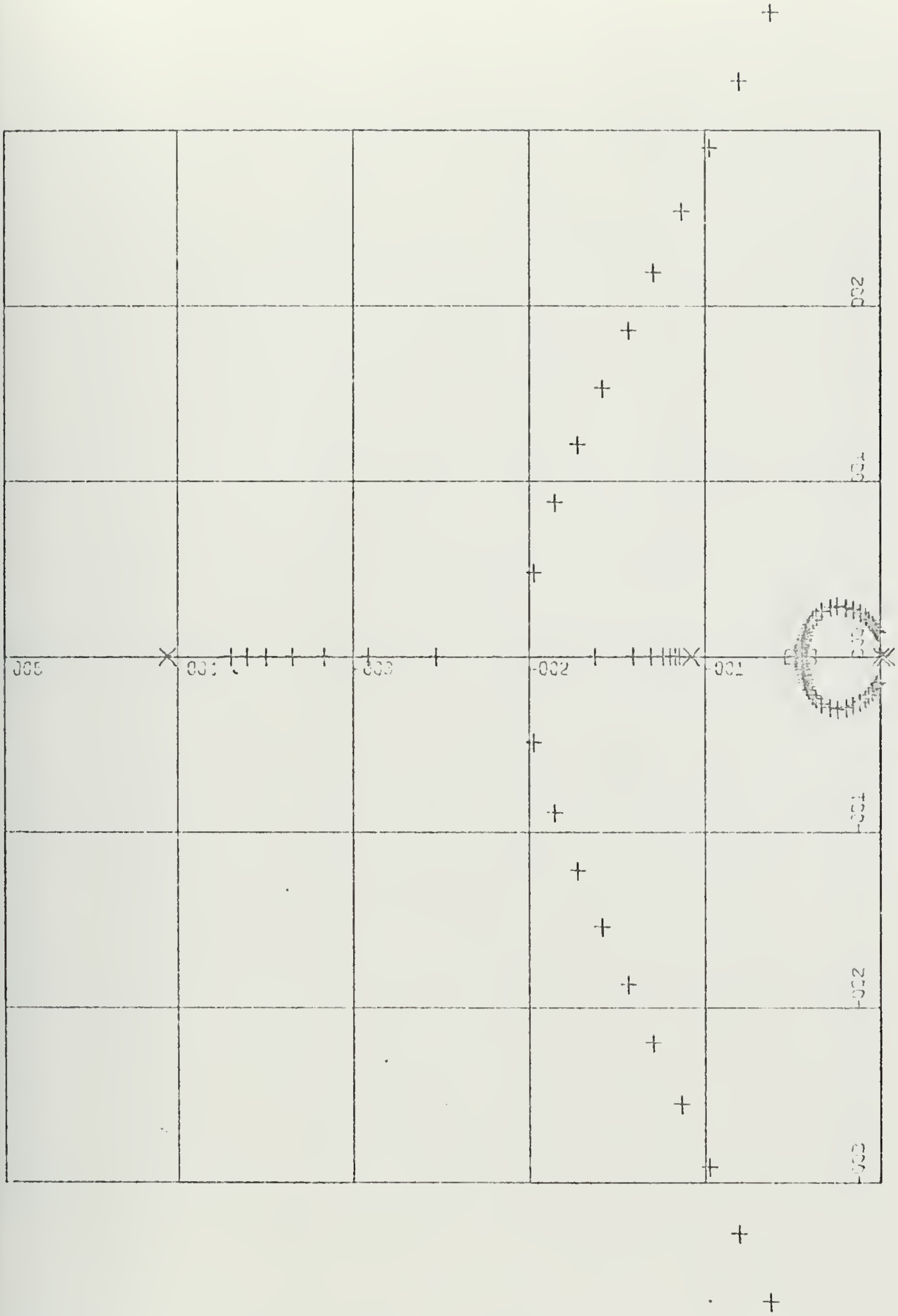
Figures 28-33 are computer outputs of the subroutine Root-Locus. They give the different system behaviour for the values of z and p selected. We can see from figures 31-33 that in order to have a good time constant we need a large value of G, while from figures 28-30 we can select very small values of G, which will give us real roots.

Having obtained the computer outputs for both types of compensation, we can observe a similarity in the system behaviour for same root location. So we can predict the same transient for step inputs. However, we need to find an optimum value of k in the case of the Rate Gyro and of z for the Filter, in order to expand the little loop in figures 21-23 and 28-30. This optimum is the best value possible to obtain and it is a compromise between a high gain and a good rudder operation, bearing in mind that for this to occur we must consider maximum deflection and rate for the rudder of this ship. Since for a quick response we need a high gain, but this could demand an excessive operation of the rudder and this could be bad for the following reasons:

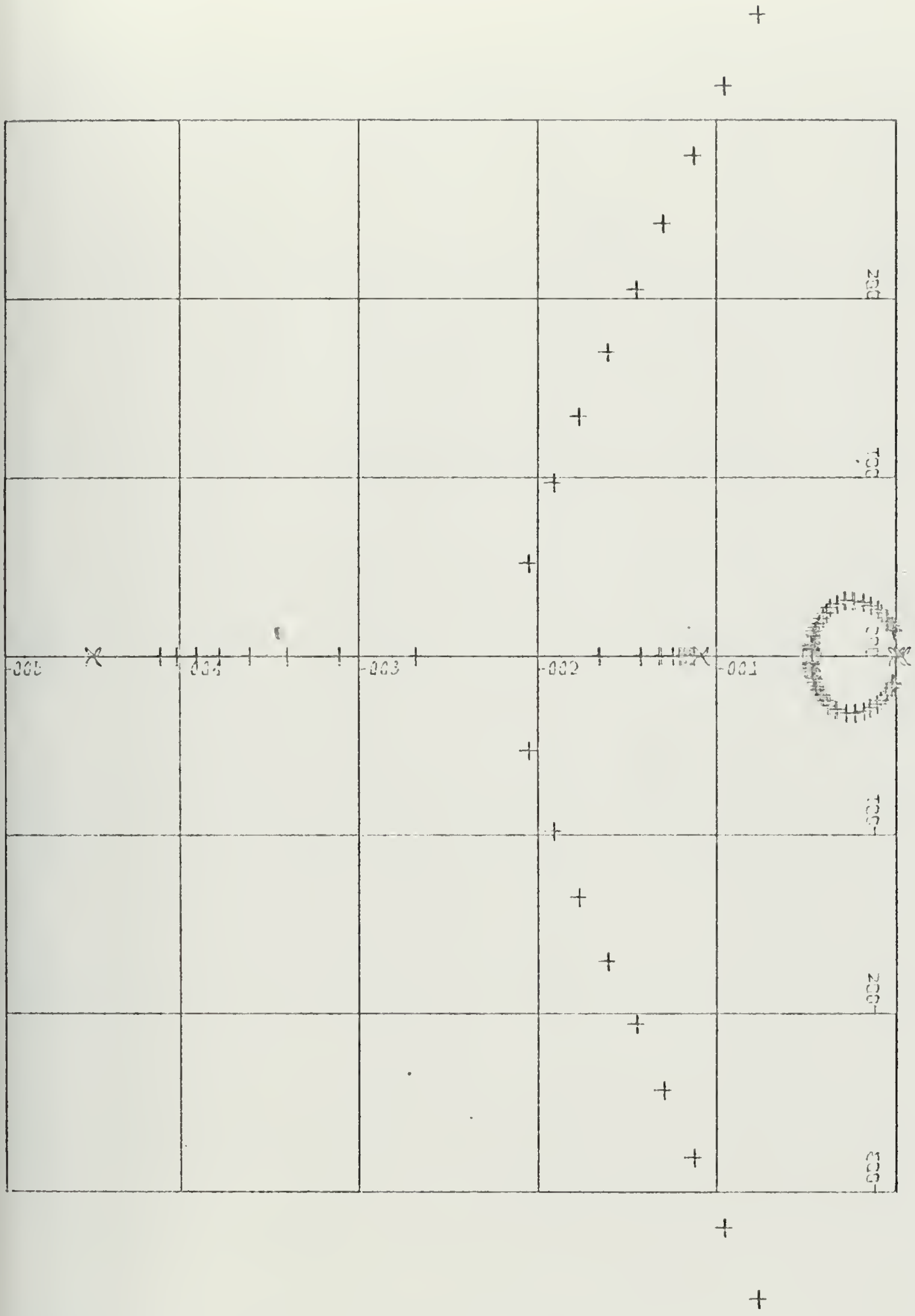
1. To get quick response we need faster rudder angle and a greater rudder angle.

2. Faster responses may cause accelerations that are too sharp for personnel on ship.

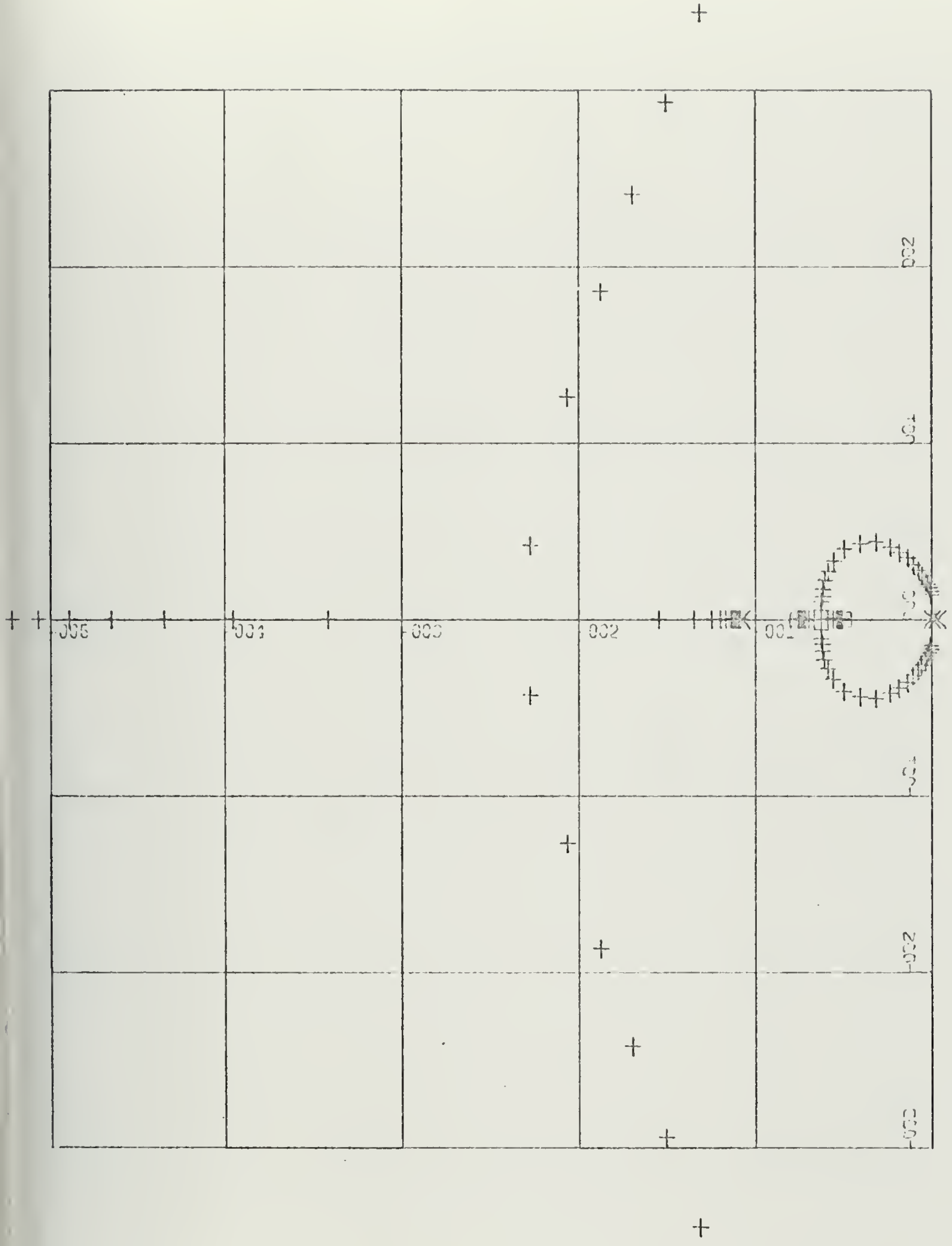
[illegible]



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS FILTER 1 COMPENSATED
AGUAYO FIGURE 28

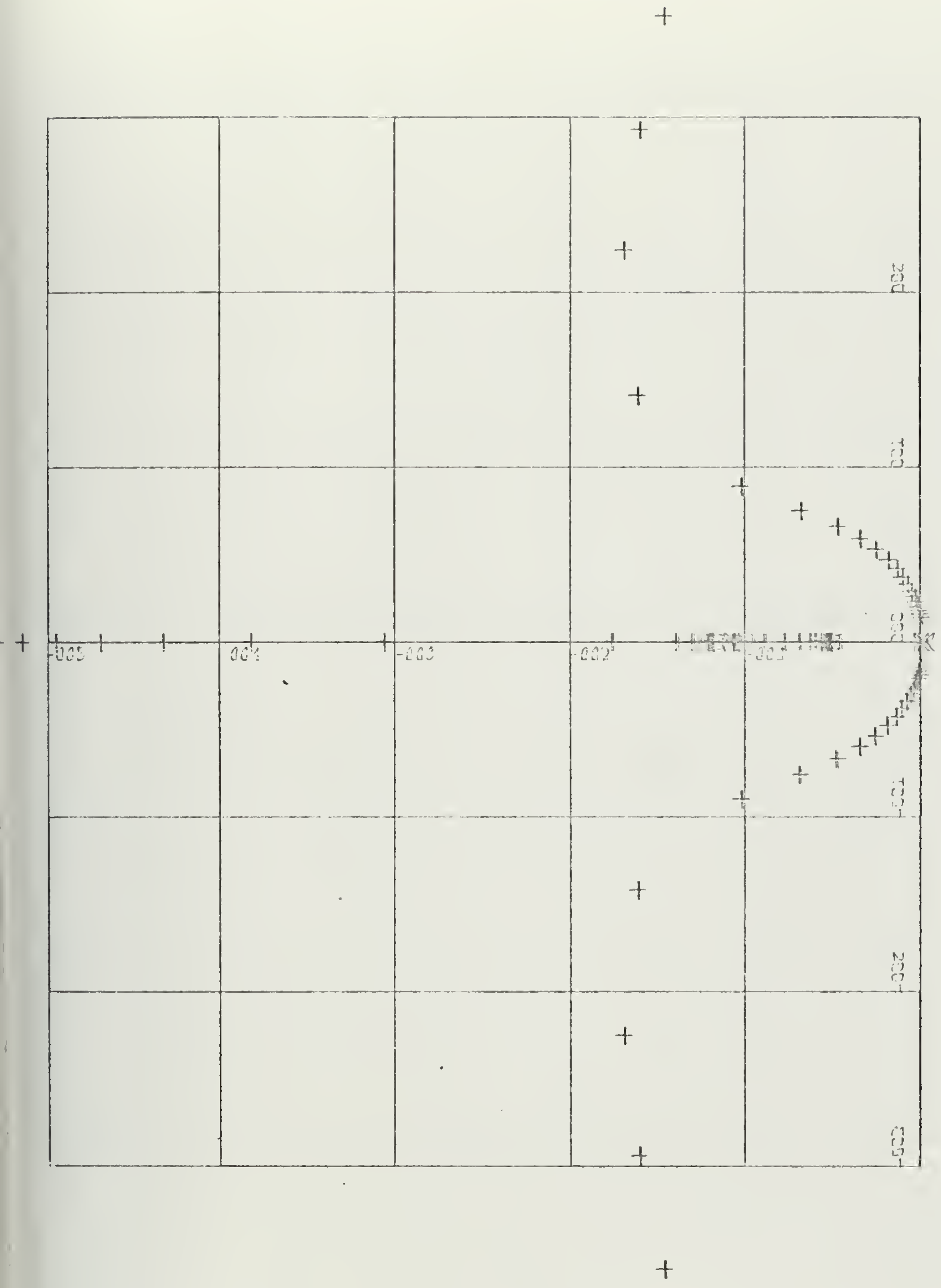


X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS FILTER 2 COMPENSATED
AGUAYO FIGURE 29

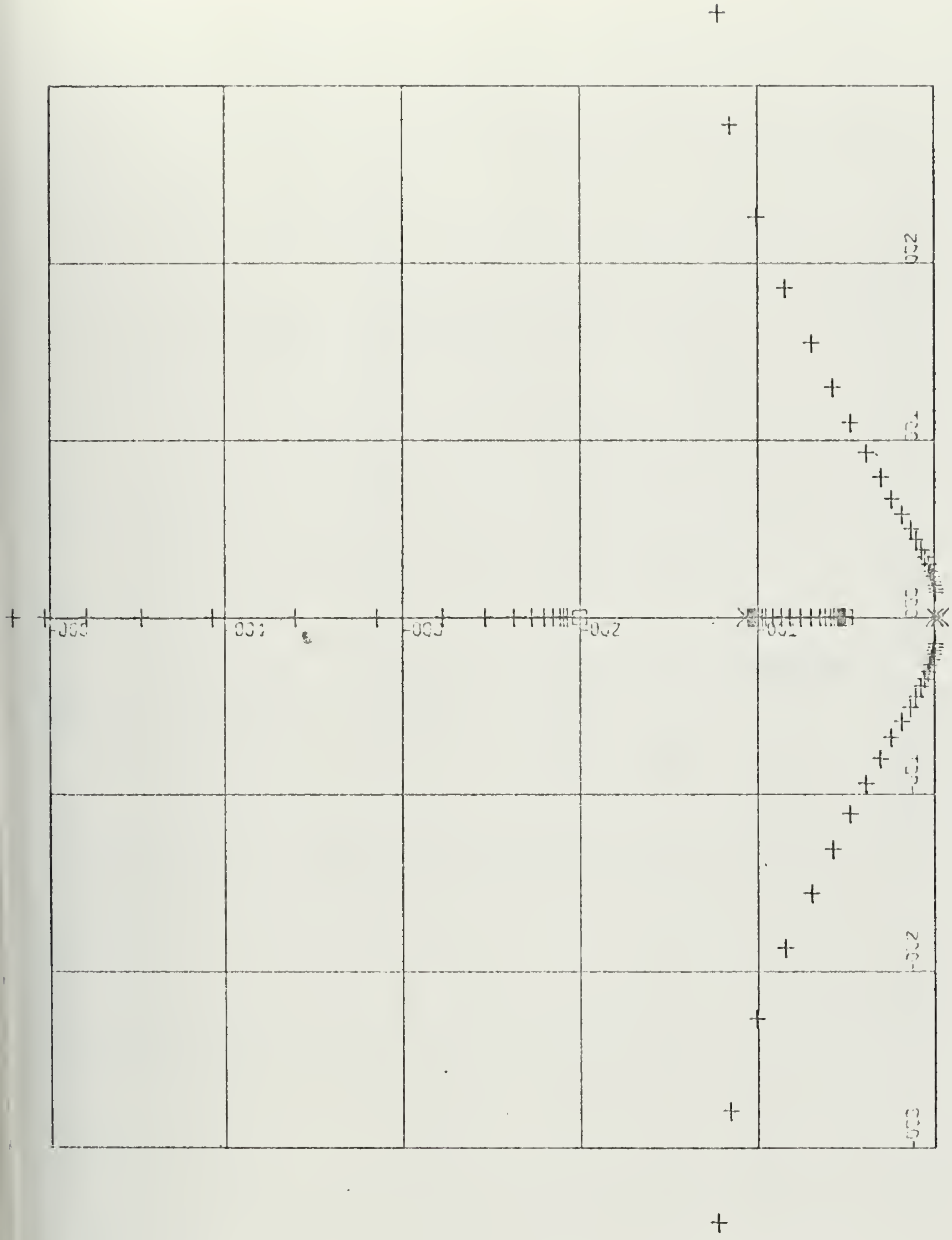


X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.

ROOT LOCUS FILTER 3 COMPENSATED
AGUAYO FIGURE 30

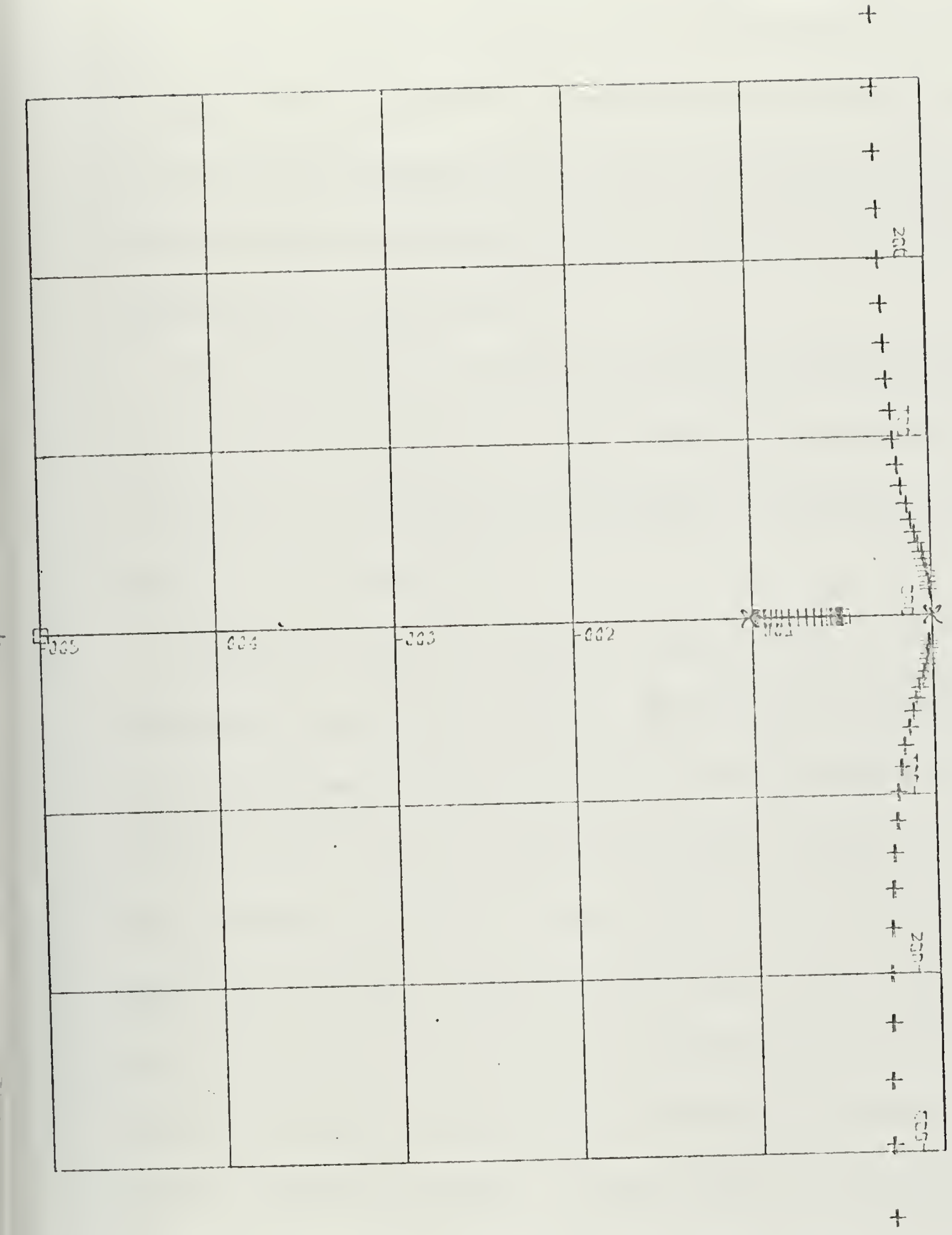


X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS FILTER 4 COMPENSATED
AGUAYO FIGURE 31



X-SCALE=1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS FILTER 5 COMPENSATED
AGUAYO . FIGURE 32

w/[illegible]



X-SCALE 1.00E-01 UNITS INCH.
Y-SCALE=1.00E-01 UNITS INCH.
ROOT LOCUS FILTER 6 COMPENSATED
AGUAYO FIGURE 33

So the next step will be to try to find the optimum value mentioned above. Right off hand we can consider the system behaviours of figures 25, 26, 32 and 33, are very much similar to our original system without compensation, so we can disregard those four systems, and now we have four different systems for the Rate Gyro and Filter compensators respectively.

We are going to simulate a disturbance that produces a rate of turn of .2 degrees/second, a value that has been found by experience can easily be reproduced on this tanker, requiring a correcting rudder angle of 10 to 20 degrees.

With this external disturbance represented as a step, we examined our eight compensated systems. By trial and error method we check for the optimum value required and we end up with a 1/k = .041 for the Rate Gyro, and a z = .041 for the Filter, which in essence are the same values we have for the case of 1/k = .04 and z = .04 for the Rate Gyro and Filter respectively, so now remain these two systems to be studied for the best gain. In all the eight initial cases we observed a common characteristic, with minor variations, that for a small variation of heading, a sudden change in rudder occurs which causes a very quick response and we may suspect an excess in both rudder parameters.

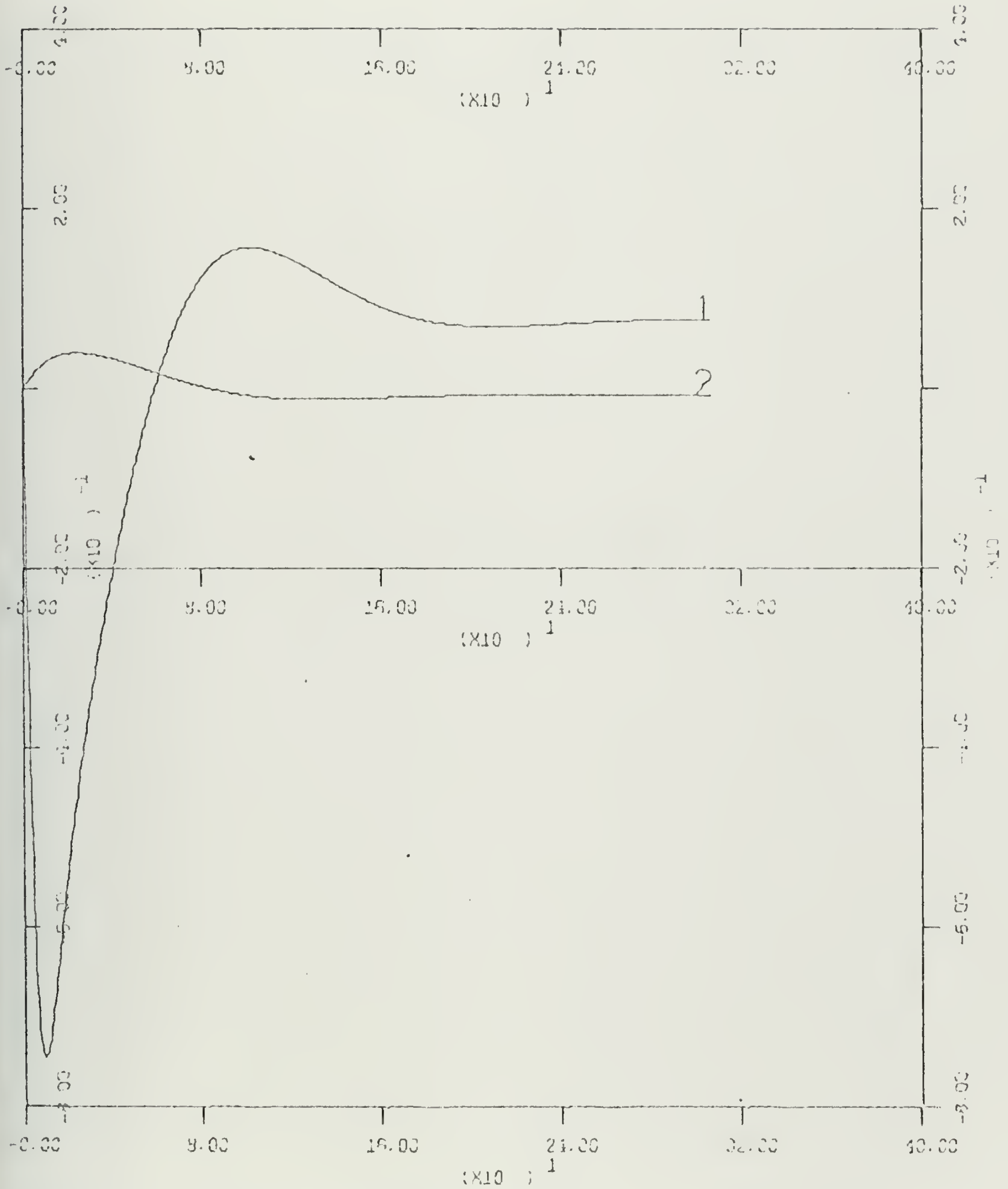
$\rightarrow k = 24.39$

Figures 34-37 are computer outputs for the system compensated with the filter, we have chosen values of gain from the root-locus

w/ [illegible]

RUDDER ANGLE, THETA VS TIME K1=9.42

AGUAYO FIGURE 34

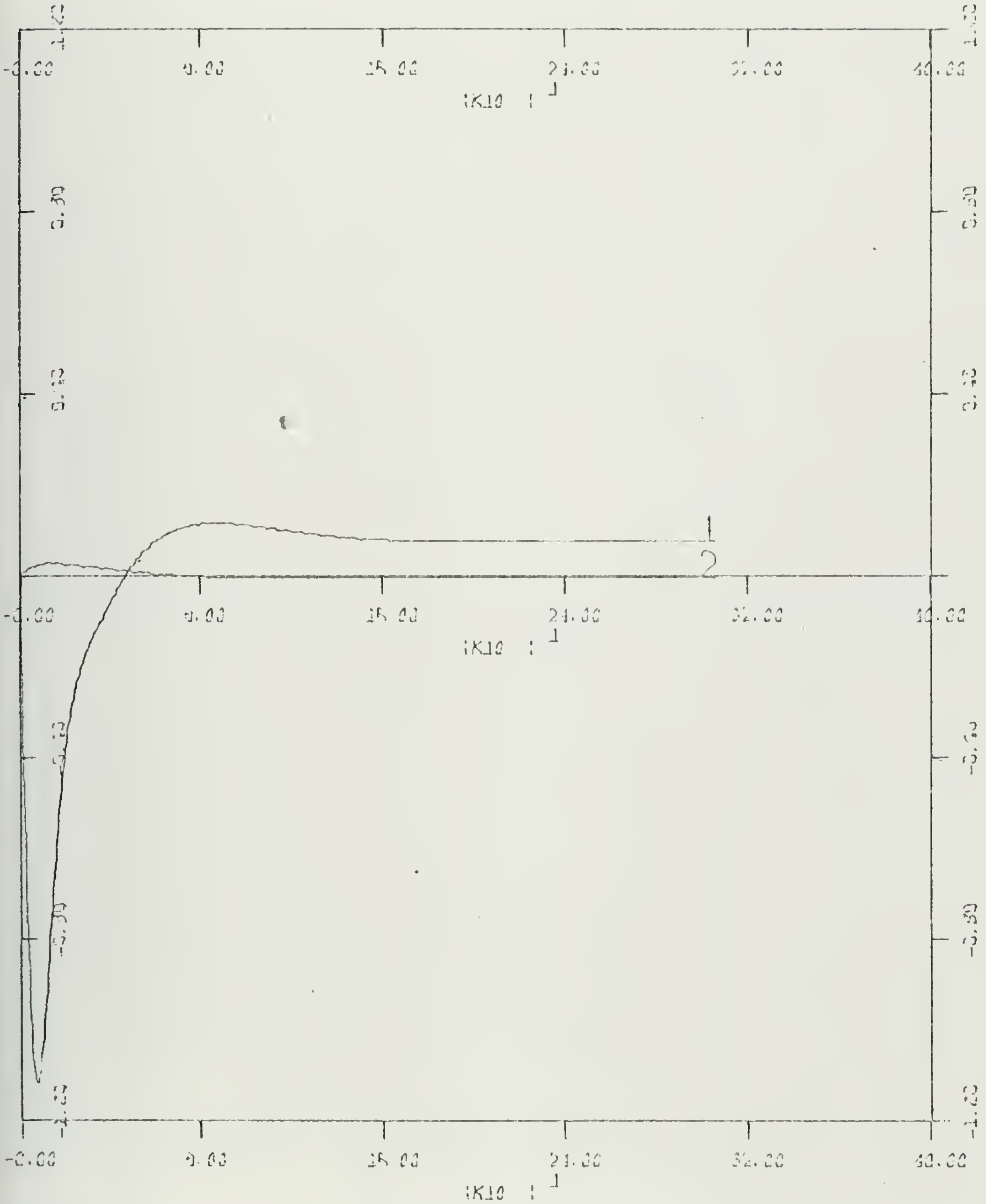


XSCALE=80.00 UNITS/INCH RUN NO.1

YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=15.87

AGUAYO FIGURE 35

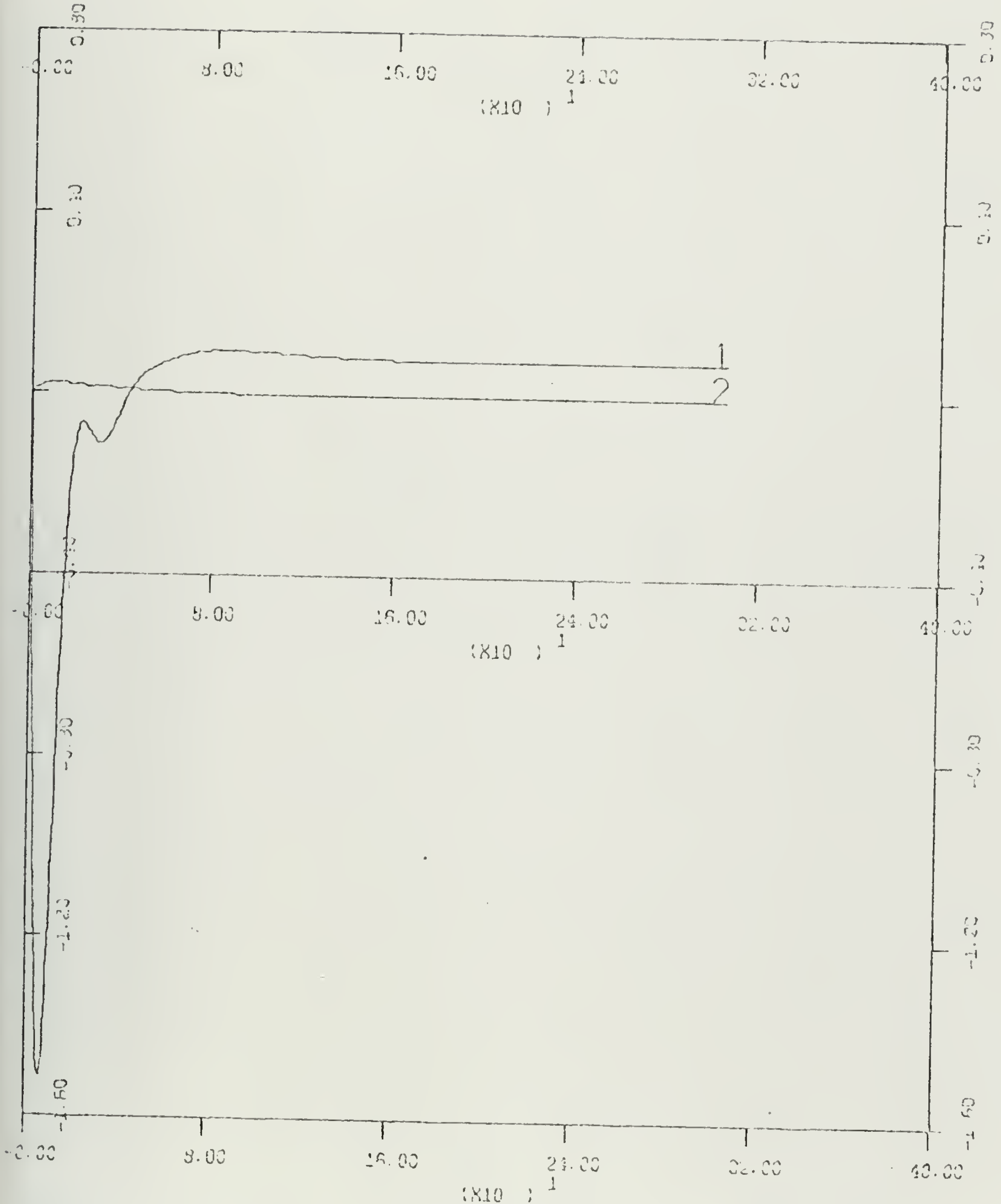


XSCALE=80.00 UNITS/INCH RUN NO.2

YSCALE=0.40 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=23.67

AGUAYO FIGURE 36

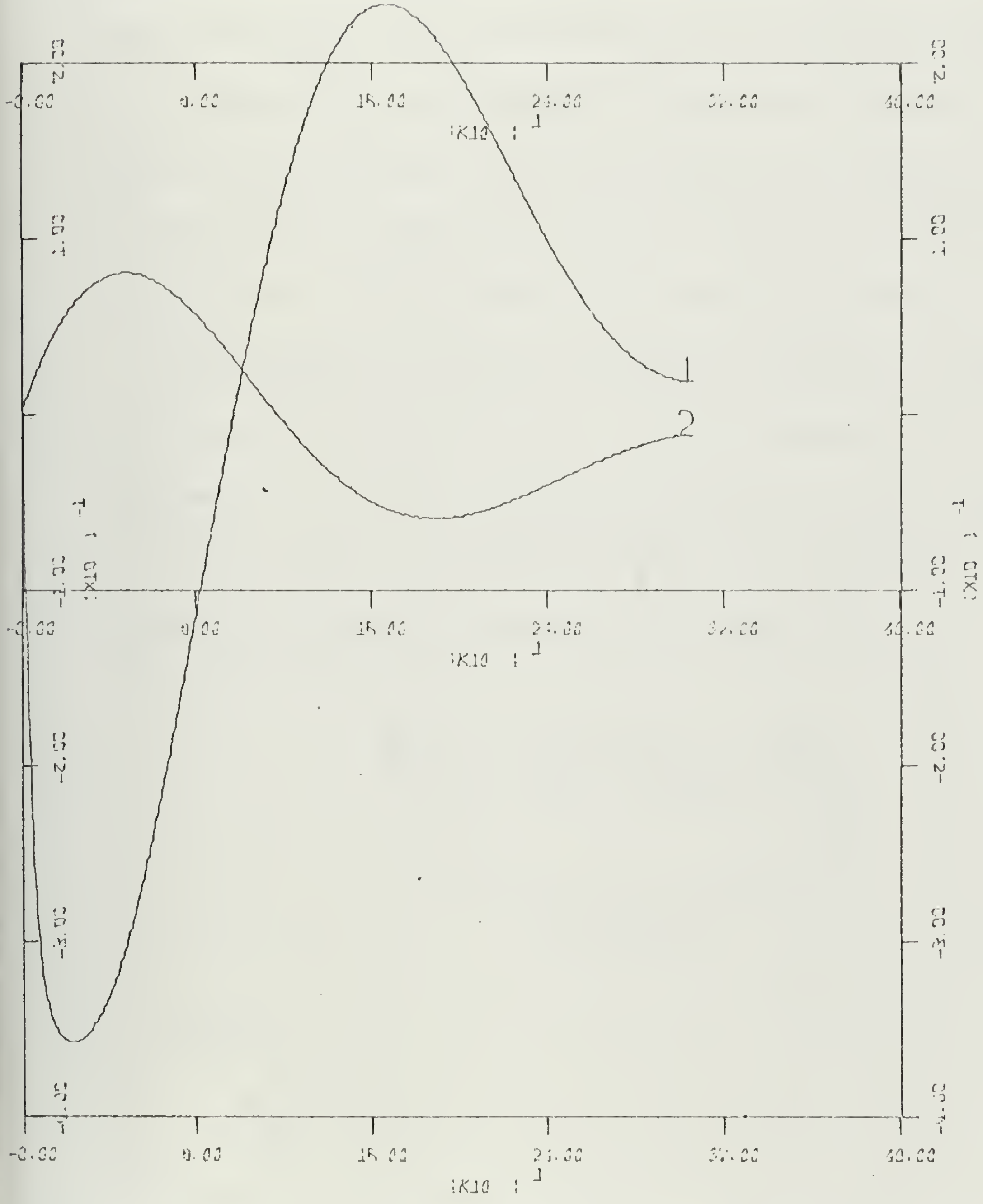


XSCALE=80.00 UNITS/INCH RUN NO.3

YSCALE=0.40 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=3.5

AGUAYO FIGURE 37



XSCALE=08.00 UNITS/INCH RUN NO.4
YSCALF=0.10 UNITS/INCH PLOT NO.1

graph, for four different damping coefficients, 9.42, 15.87, 23.67 and 3.5 respectively. We can observe from the first three figures that a quick response is obtained and steady state is obtained in a very short time, but this could exceed the restrictions of the rudder.

In figure 37 we see a moderate response and we do not reach the steady state at the end of the simulated time, which is only 5 minutes, as expected for a ship of characteristics such as this. We need to verify if there is any violation of the rudder restrictions.

With the help of computer simulation, a program in DSL, which is given at the end of the thesis, is used to simulate limiters for both parameters. In order to introduce the limiting value of Rudder Rate, we need to replace, in the block diagram, the steering Gear transfer function for a circuit equivalent, given in figure 38:

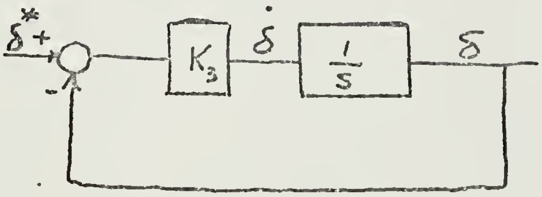


FIGURE 38

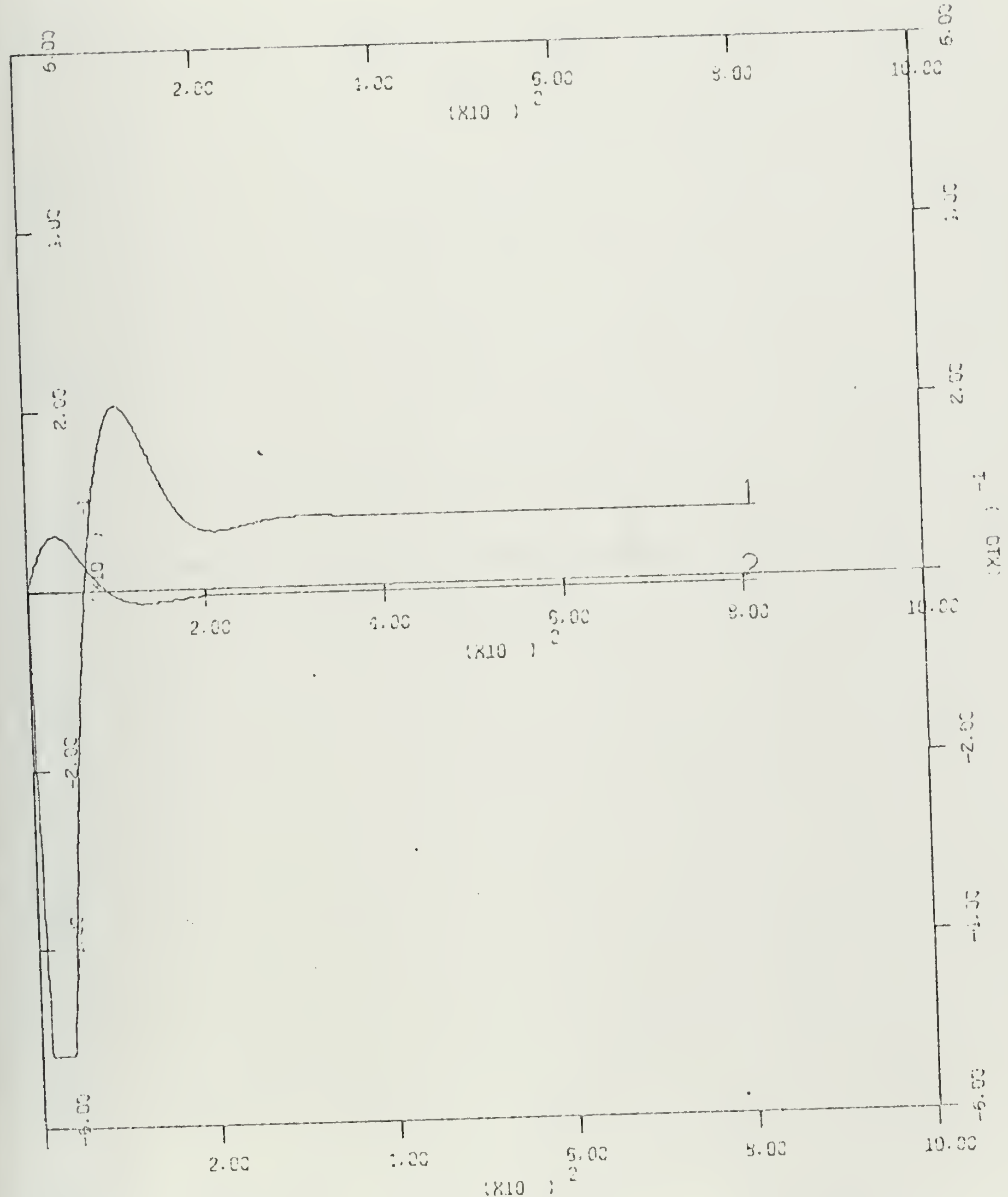
where

$$K_3 = 1/T_E$$

With the program above mentioned and the values of gain selected before we obtain the figures 39-42, computer outputs, where we see

RUDDER ANGLE, THETA VS TIME K1=9.42

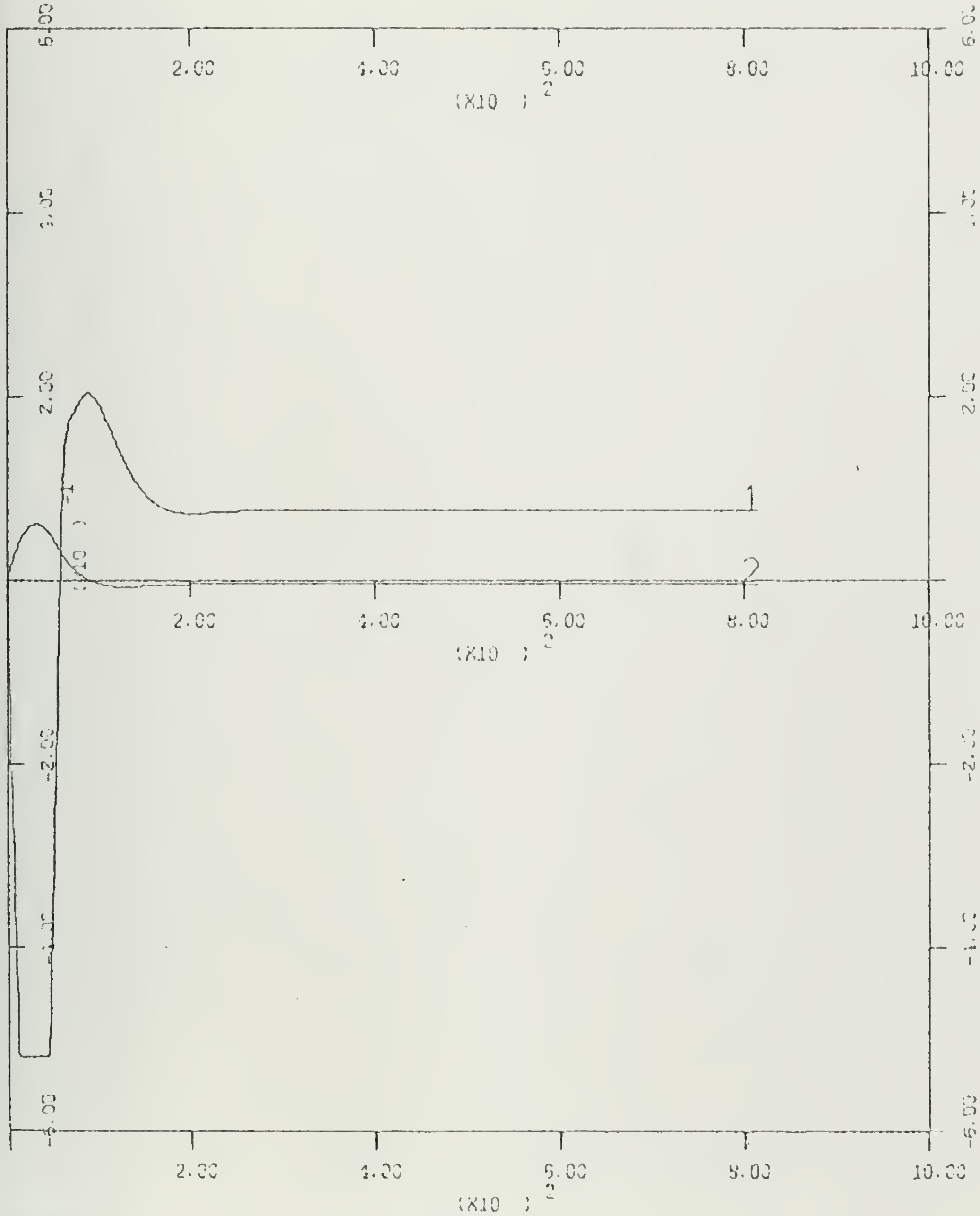
AGUAYO FIGURE 39



XSCALE=200.00 UNITS/INCH RUN NO. 1
YSCALE=0.20 UNITS/INCH PLOT NO. 1

RUDDER ANGLE, THETA VS TIME K1=15.87

AGUAYO FIGURE 40



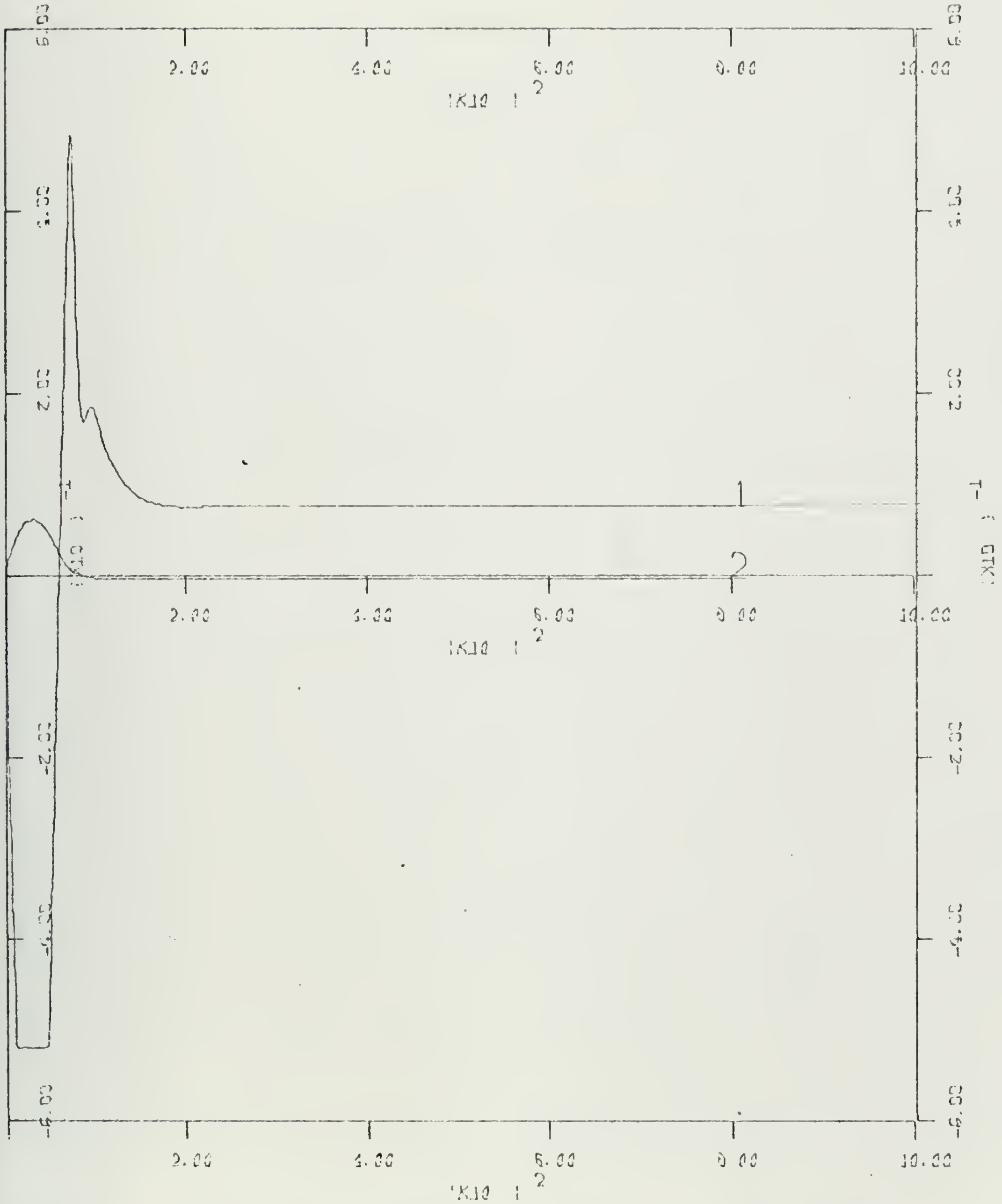
XSCALE=200.00 UNITS/INCH RUN NO.2

YSCALE=0.20 UNITS/INCH PLOT NO.1

w/ [illegible]

RUDDER ANGLE, THETA VS TIME K1=23.67

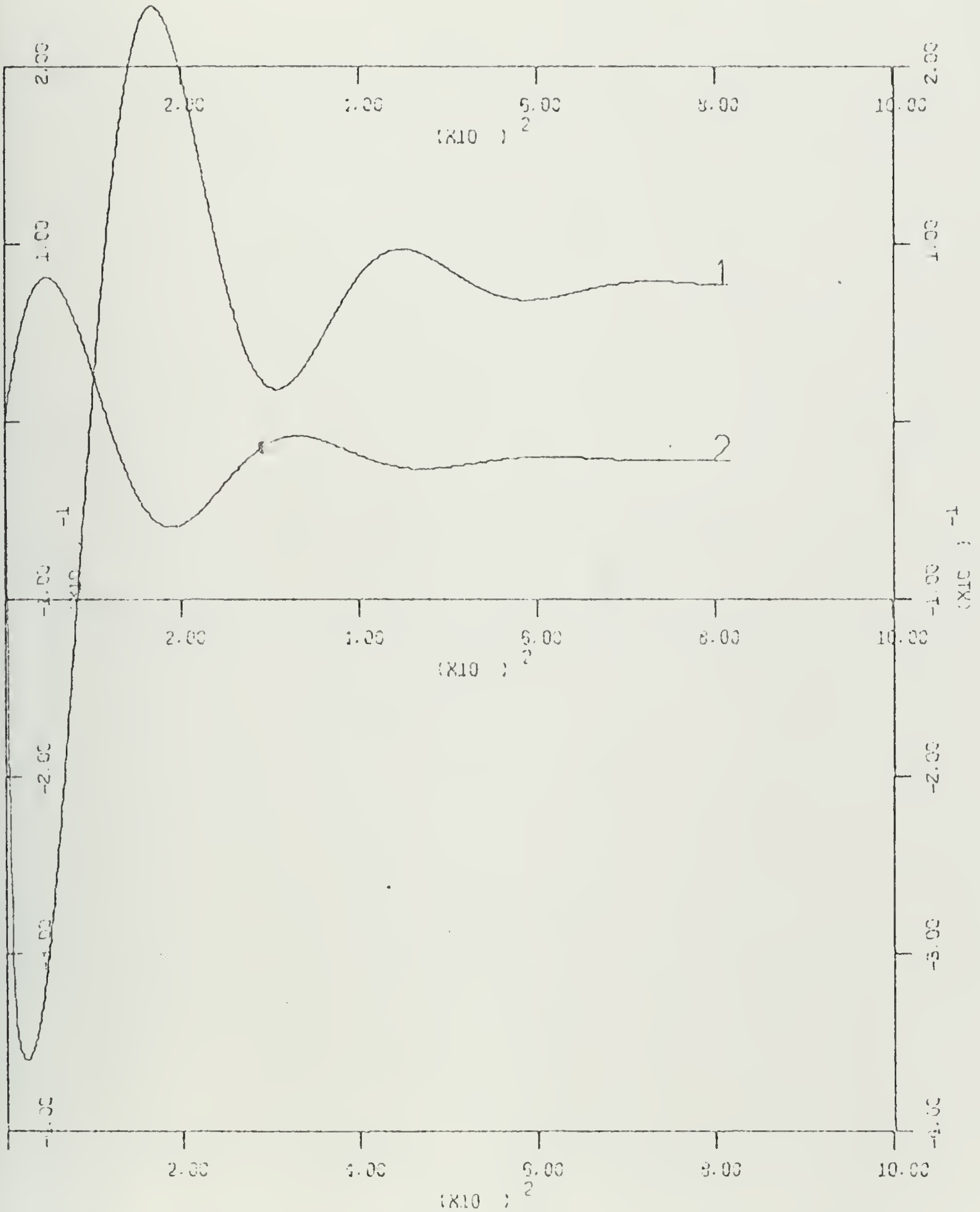
AGUAYO FIGURE 41



XSCALE=200.00 UNITS/INCH RUN NO.3
YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=3.5

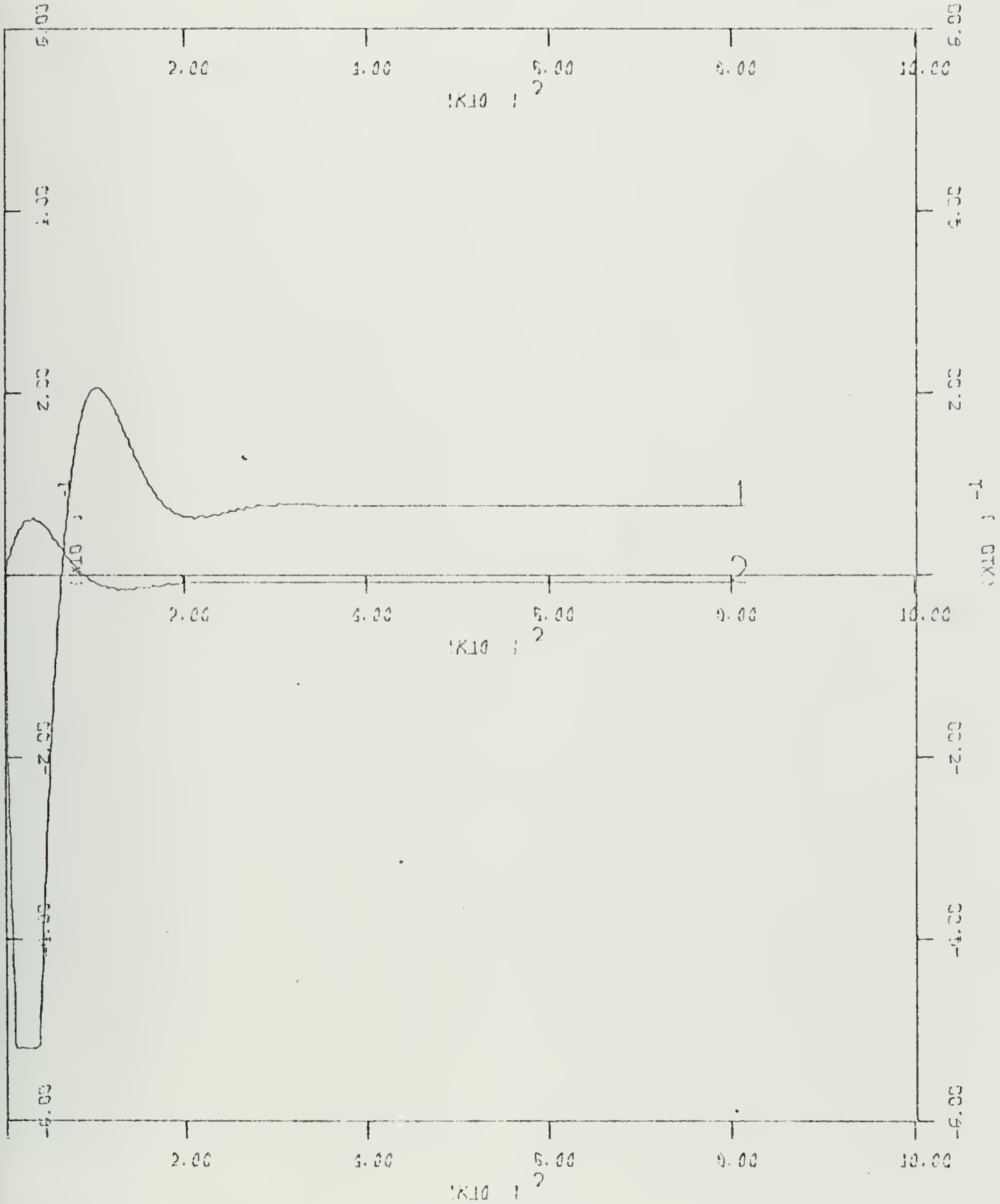
AGUAYO FIGURE 42



XSCALE=200.00 UNITS/INCH RUN NO.4
YSCALE=0.10 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=6.

AGUAYO FIGURE 43

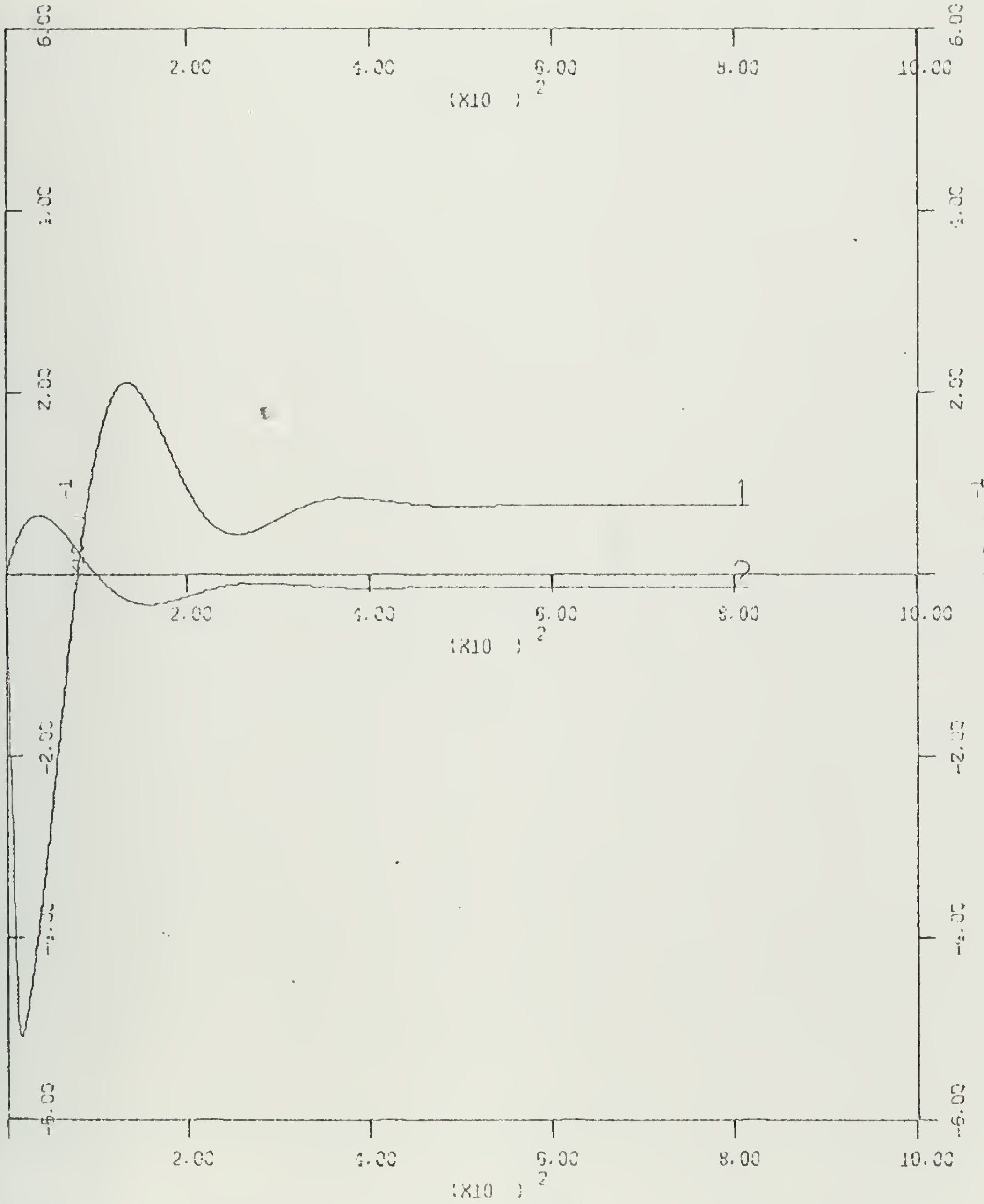


XSCALE=200.00 UNITS/INCH RUN NO.1

YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=5.3

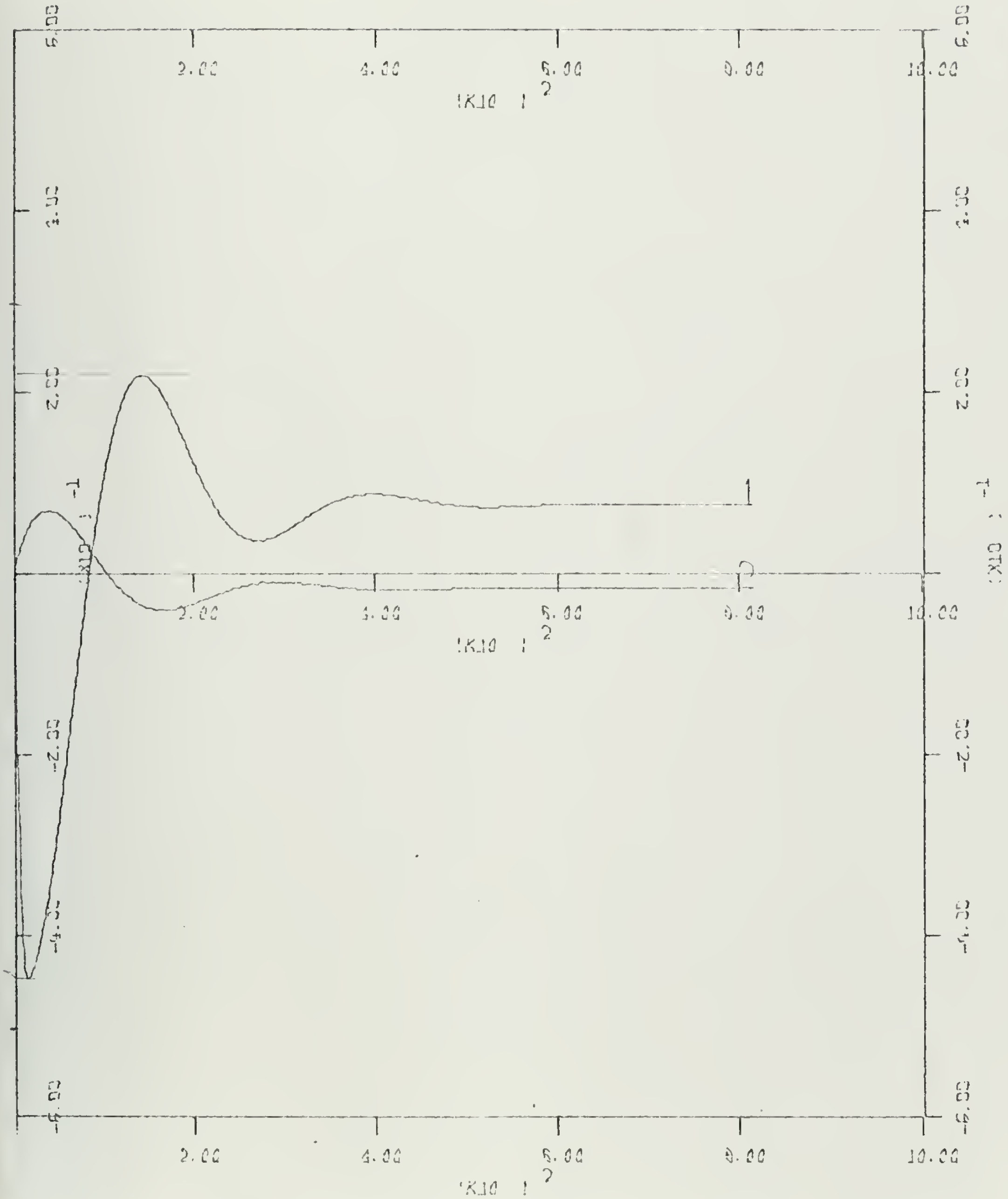
AGUAYO FIGURE 44



XSCALE=200.00 UNITS/INCH RUN NO.2
YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=4.6

AGUAYO FIGURE 45



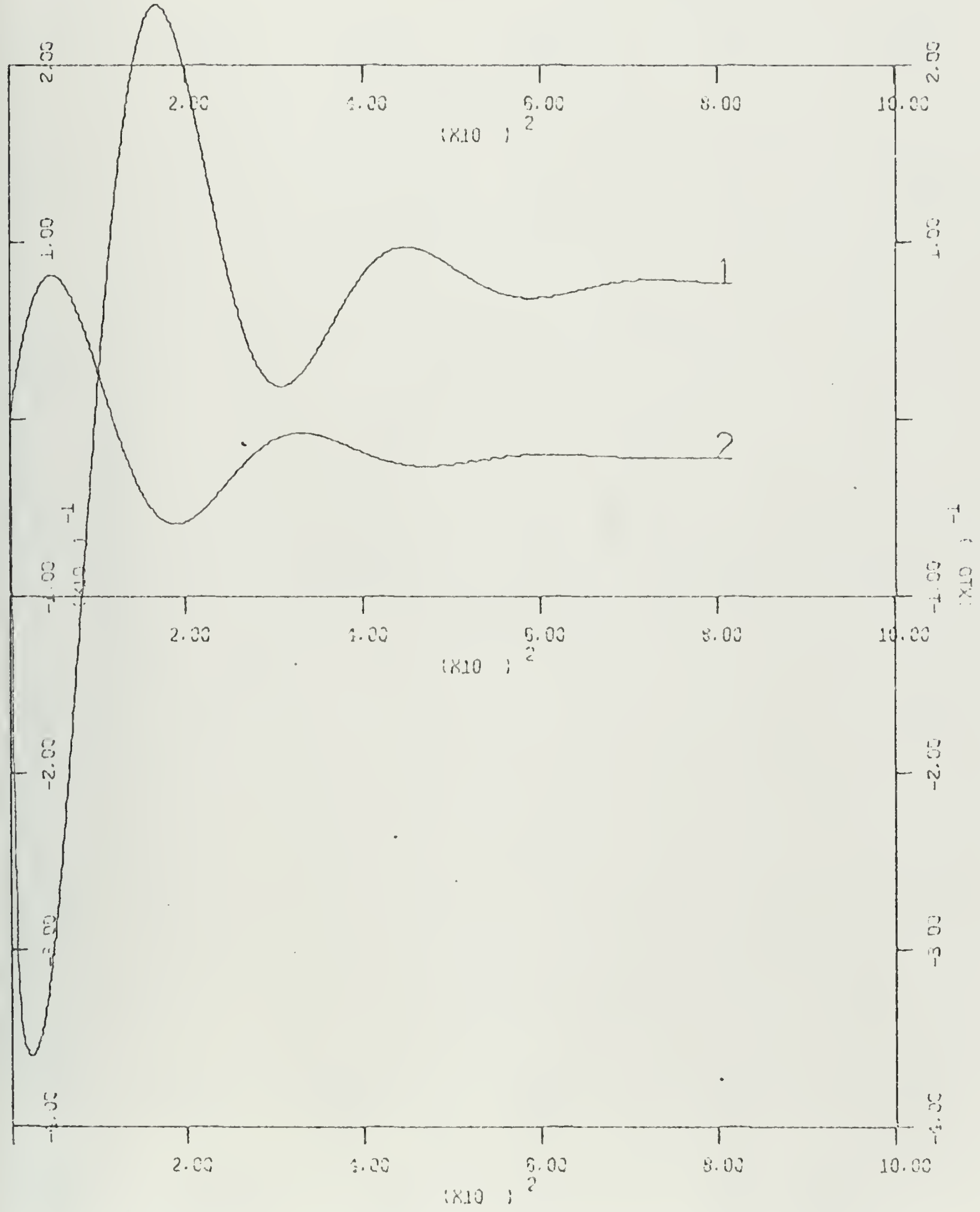
XSCALE=200.00 UNITS/INCH RUN NO.3

YSCALE=0.20 UNITS/INCH PLOT NO.1

with filter

RUDDER ANGLE, THETA VS TIME K1=3.5

AGUAYO FIGURE 46

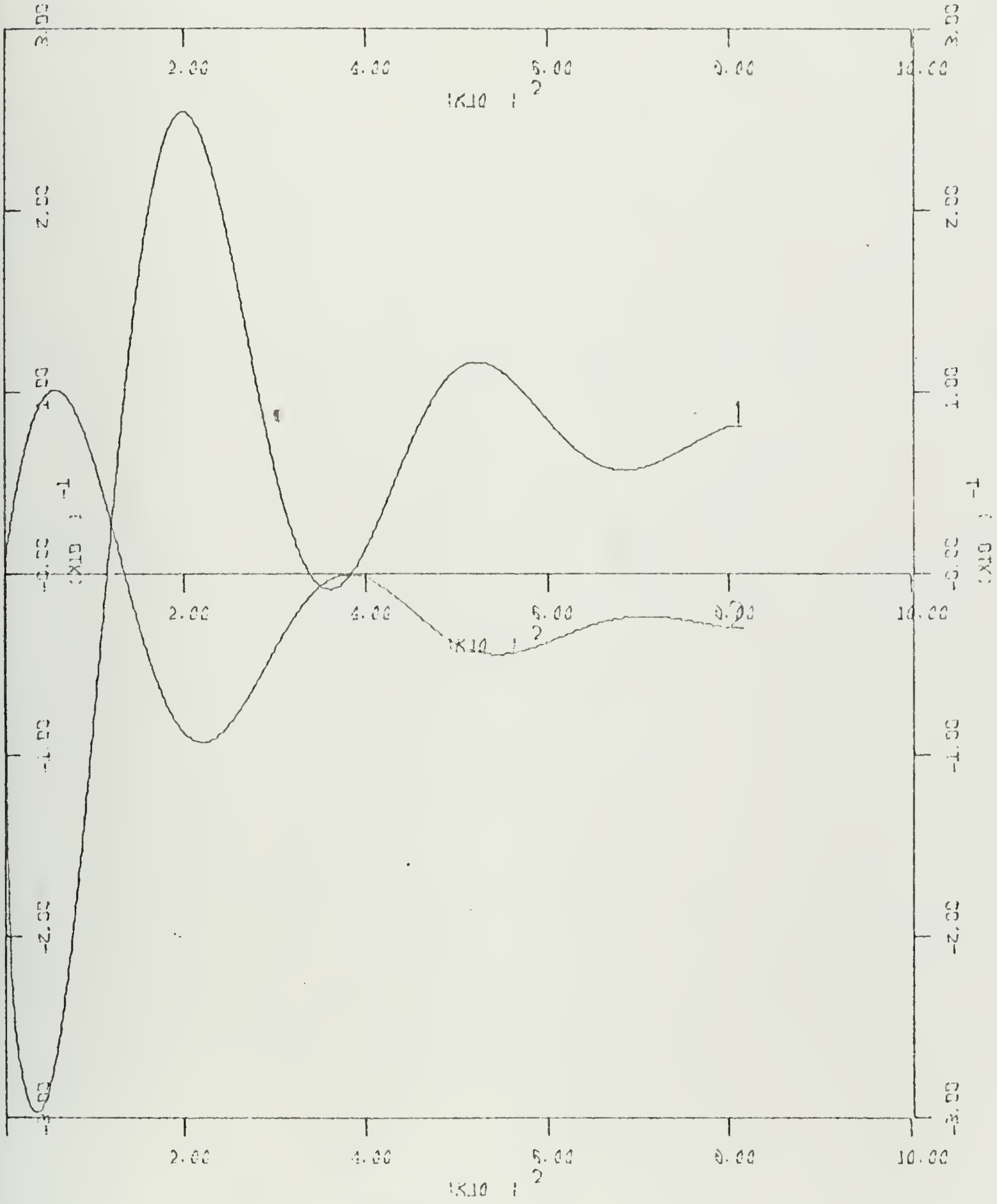


XSCALE=200.00 UNITS/INCH RUN NO.4
YSCALE=0.10 UNITS/INCH PLOT NO.1

with friction

RUDDER ANGLE, THETA VS TIME K1=2.5

AGUAYO FIGURE 47

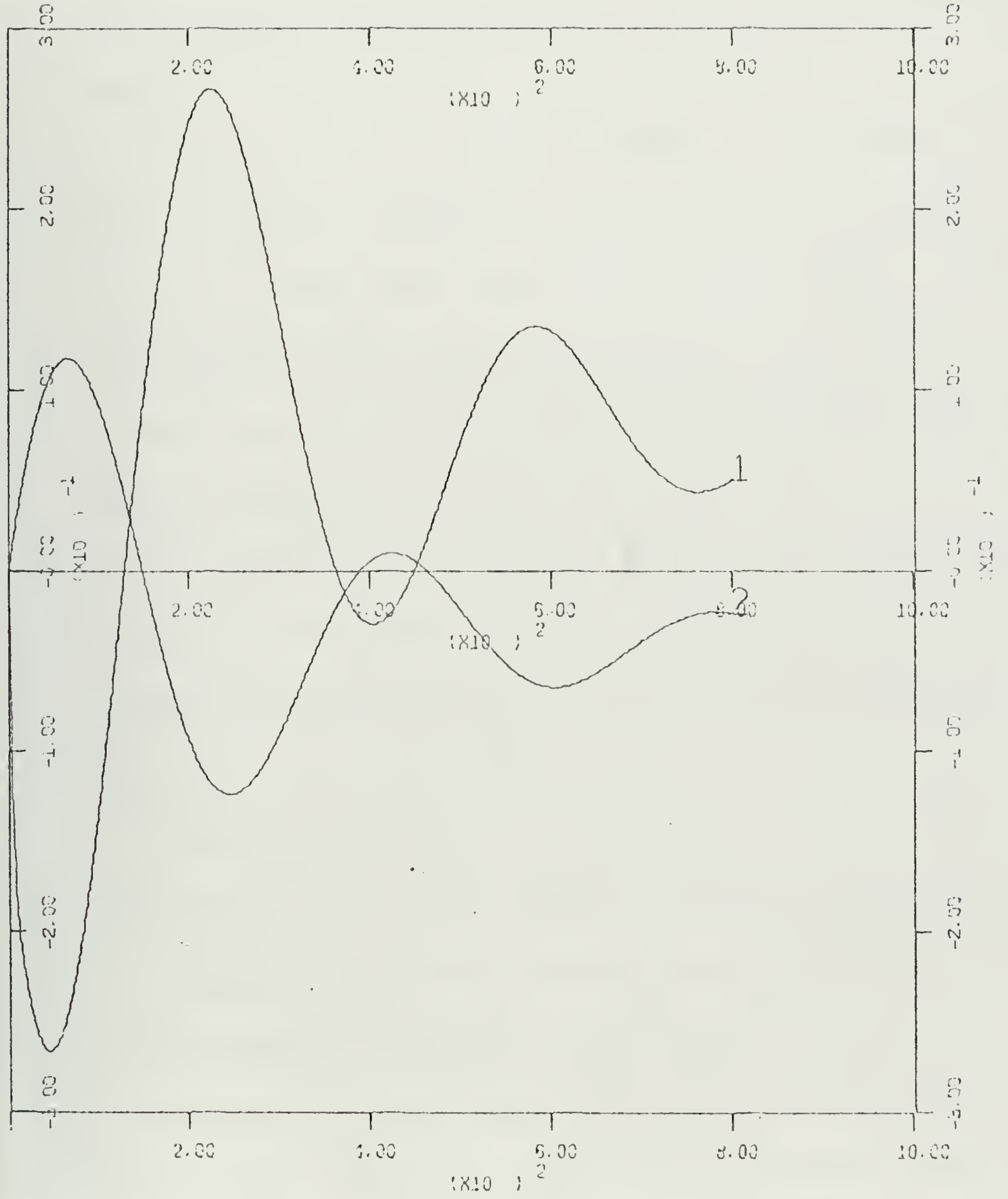


XSCALE=200.00 UNITS/INCH RUN NO.5
YSCALE=0.10. UNITS/INCH PLOT NO.1

with filter

RUDDER ANGLE, THETA VS TIME K1=2.

AGUAYO FIGURE 48



XSCALE=200.00 UNITS/INCH RUN NO.6
YSCALE=0.10 UNITS/INCH PLOT NO.1

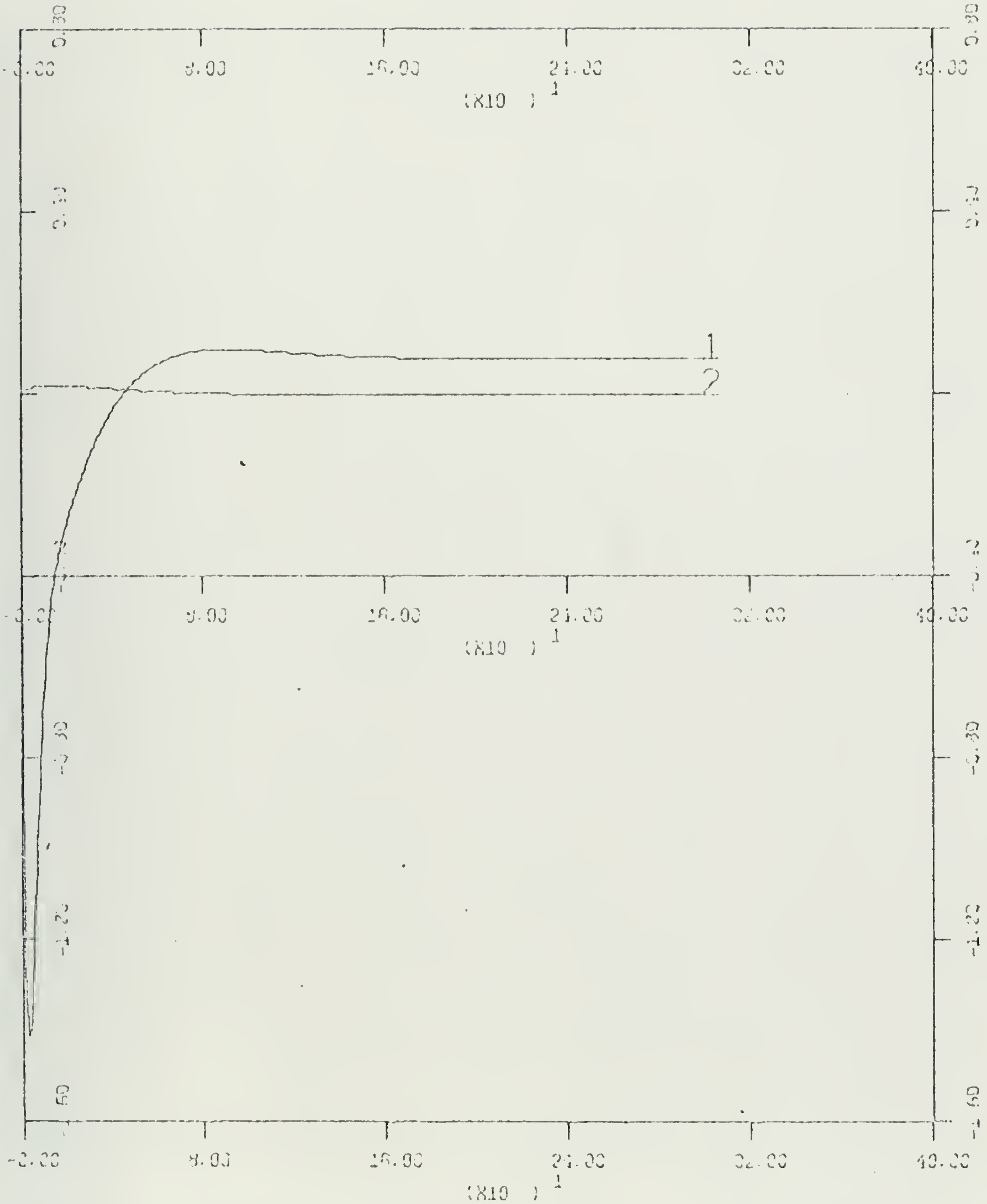
in the first figures that even if the system is stabilized, there is a portion of the response where we exceed the rudder deflection, while in figure 42 we see a smooth settle down without any clipping. Will be a good idea to try values of gain within this small range of gain values.

Figures 43-48 are computer outputs for the system above mentioned with values of gain of 6., 5.3, 4.6, 3.5, 2.5 and 2. We can observe in figure 44 for a gain value of 5.3 we obtain a good settling time with the smaller steady state error of only .8 of degree out of course which is excellent, but we have some rudder action even after settling time. In figure 45 for a gain value of 4.6 we obtain a steady state error of 1.03 degree out of course, with a settling time of about 2 more minutes than for the former case, but we get smaller rudder deflections. So we can conclude that this value of 4.6 will be the best value for this system.

Now considering the Rate Gyro having a zero at 1/k = .04, with the same disturbance, we obtain the computer outputs of figures 49-52, for values of gain selected from the Root-Locus graph, for four different damping coefficient, 22.26, 67.28, 35.29 and 3.5 respectively, we observe almost the same results as in the case of the Filter, i.e., the first three figures evidently violate the rudder restrictions and only in figure 51 for a gain value of 3.5 gives us a good system operating under real conditions. Figures 53-58 are computer outputs

RUDDER ANGLE, THETA VS TIME K1=22.26

AGUAYO FIGURE 49

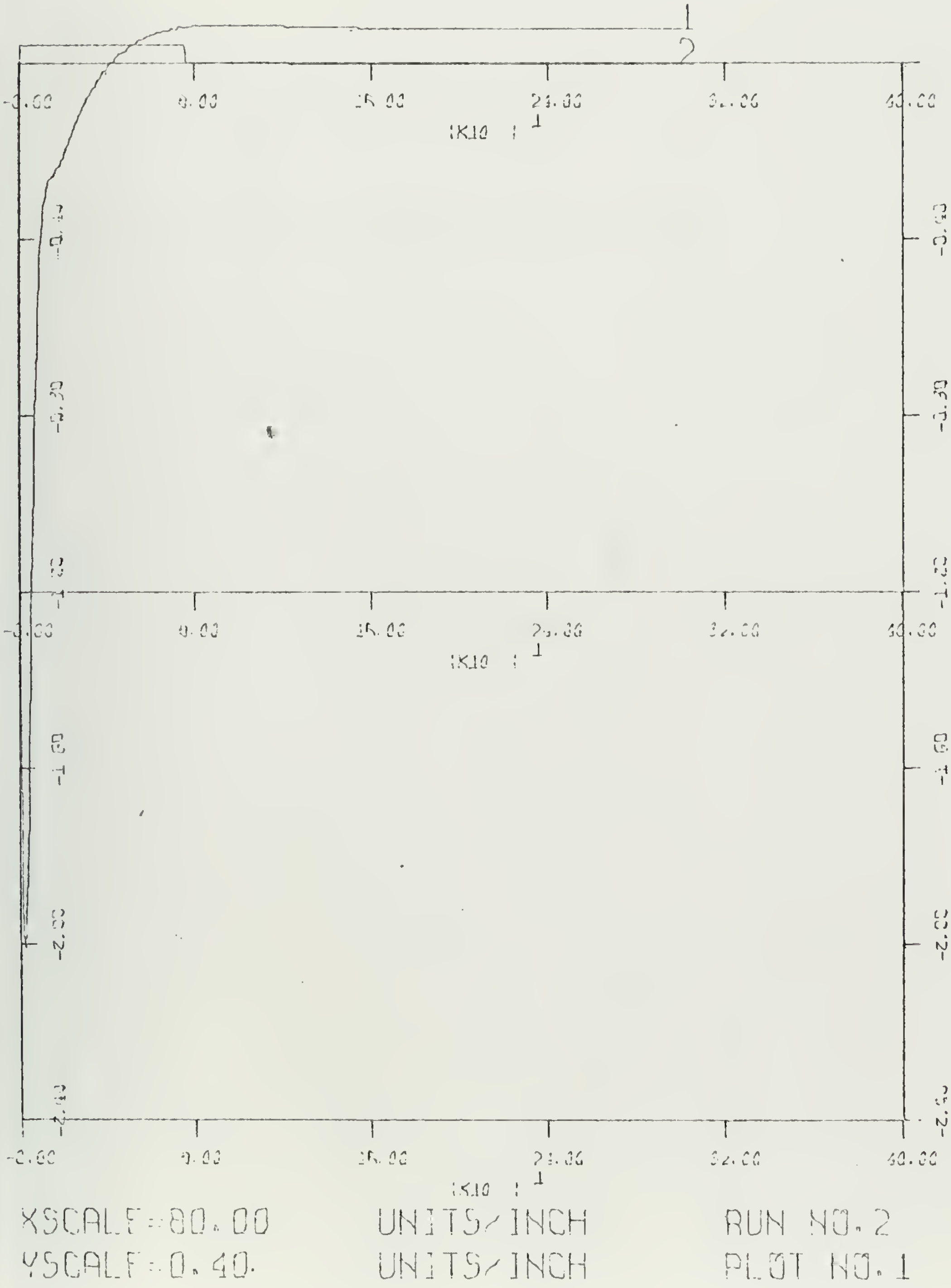


XSCALE=80.00 UNITS/INCH RUN NO. 1

YSCALE=0.40 UNITS/INCH PLOT NO. 1

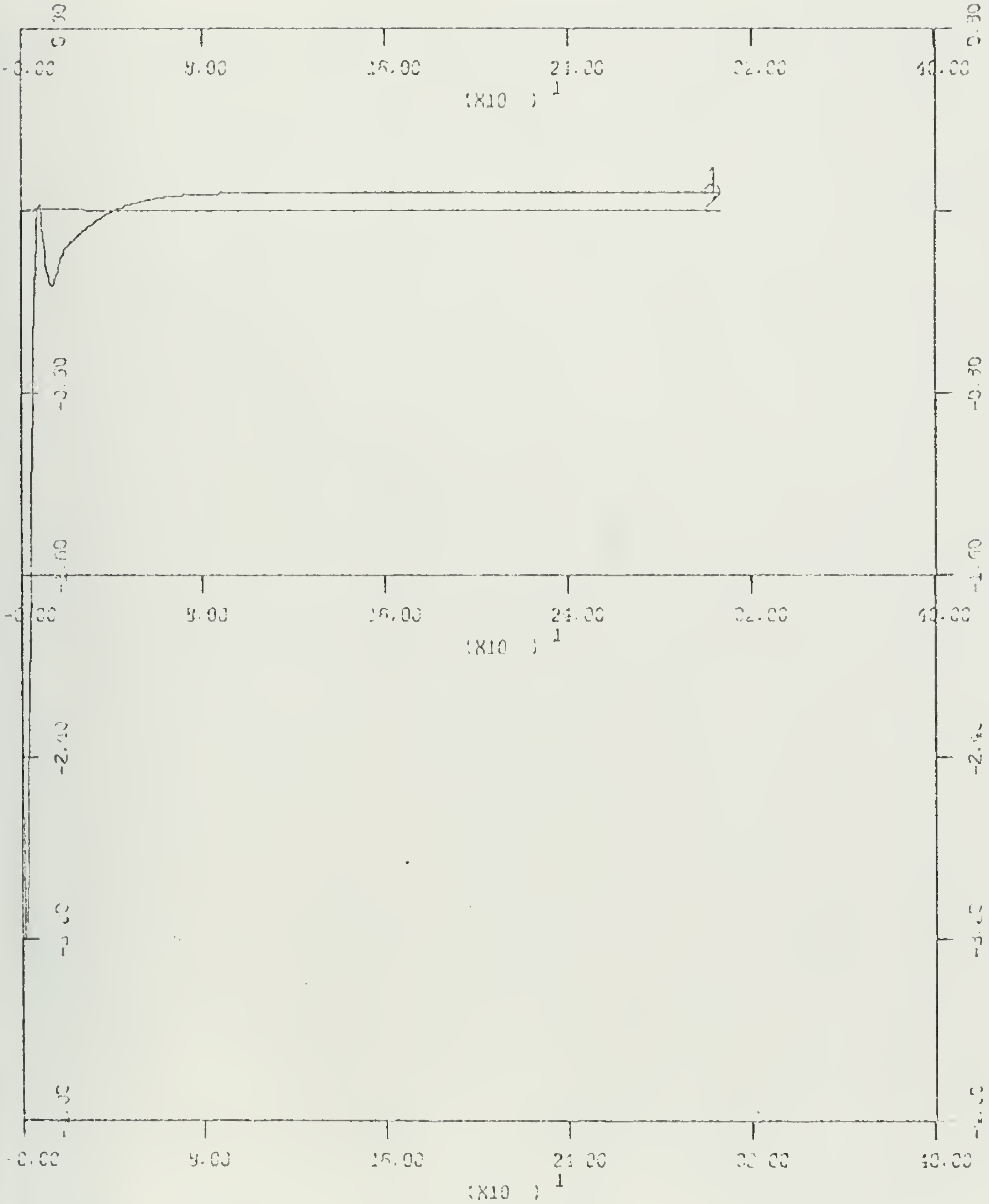
RUDDER ANGLE, THETA VS TIME K1=35.29

AGUAYO FIGURE 50



RUDDER ANGLE, THETA VS TIME K1=67.28

AGUAYO FIGURE 51

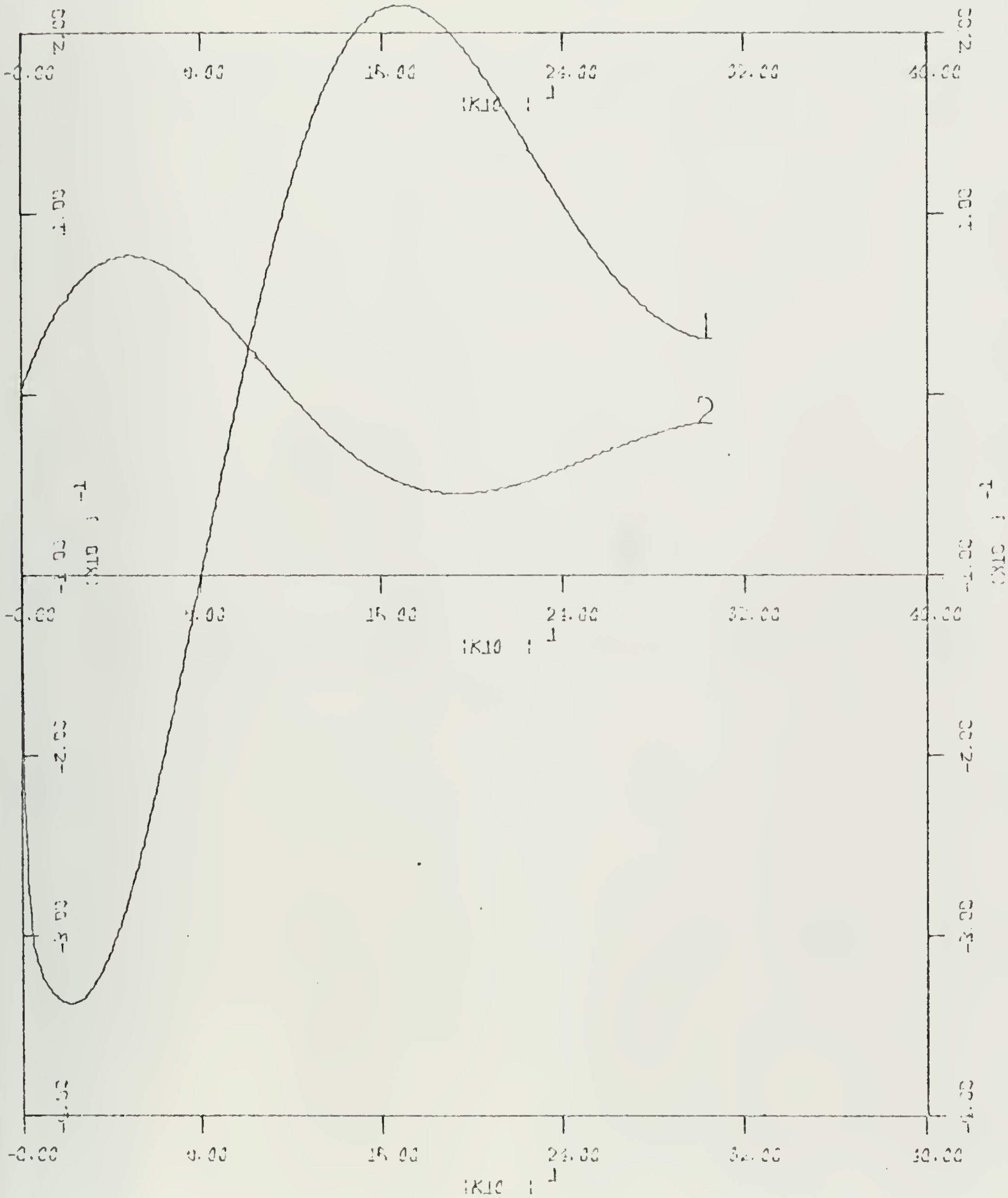


XSCALE=80.00 UNITS/INCH RUN NO.3

YSCALE=0.80 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=3.5

AGUAYO FIGURE 52

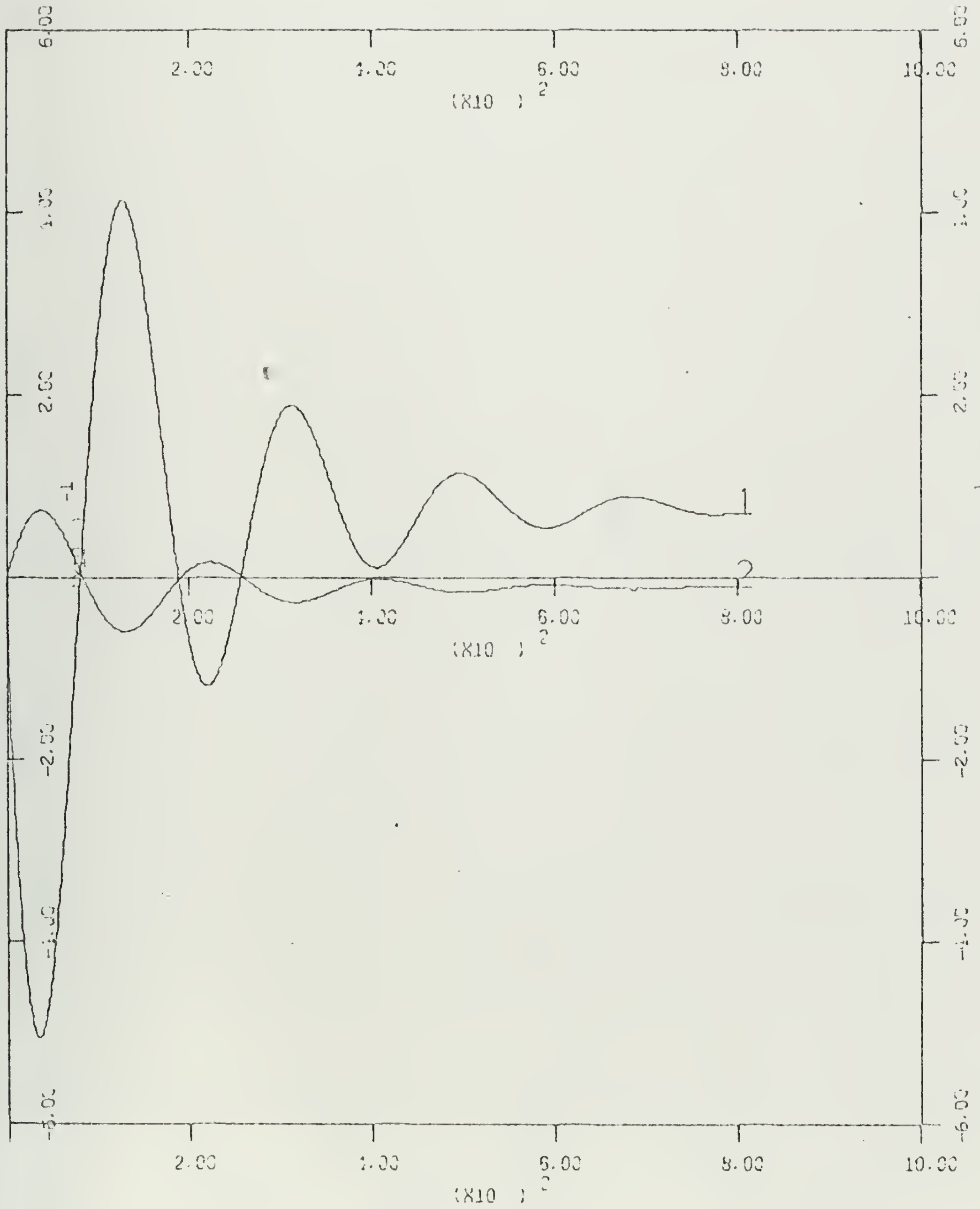


XSCALE=80.00 UNITS/INCH RUN NO.4

YSCALE=0.10 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1=6.2

AGUAYO FIGURE 53

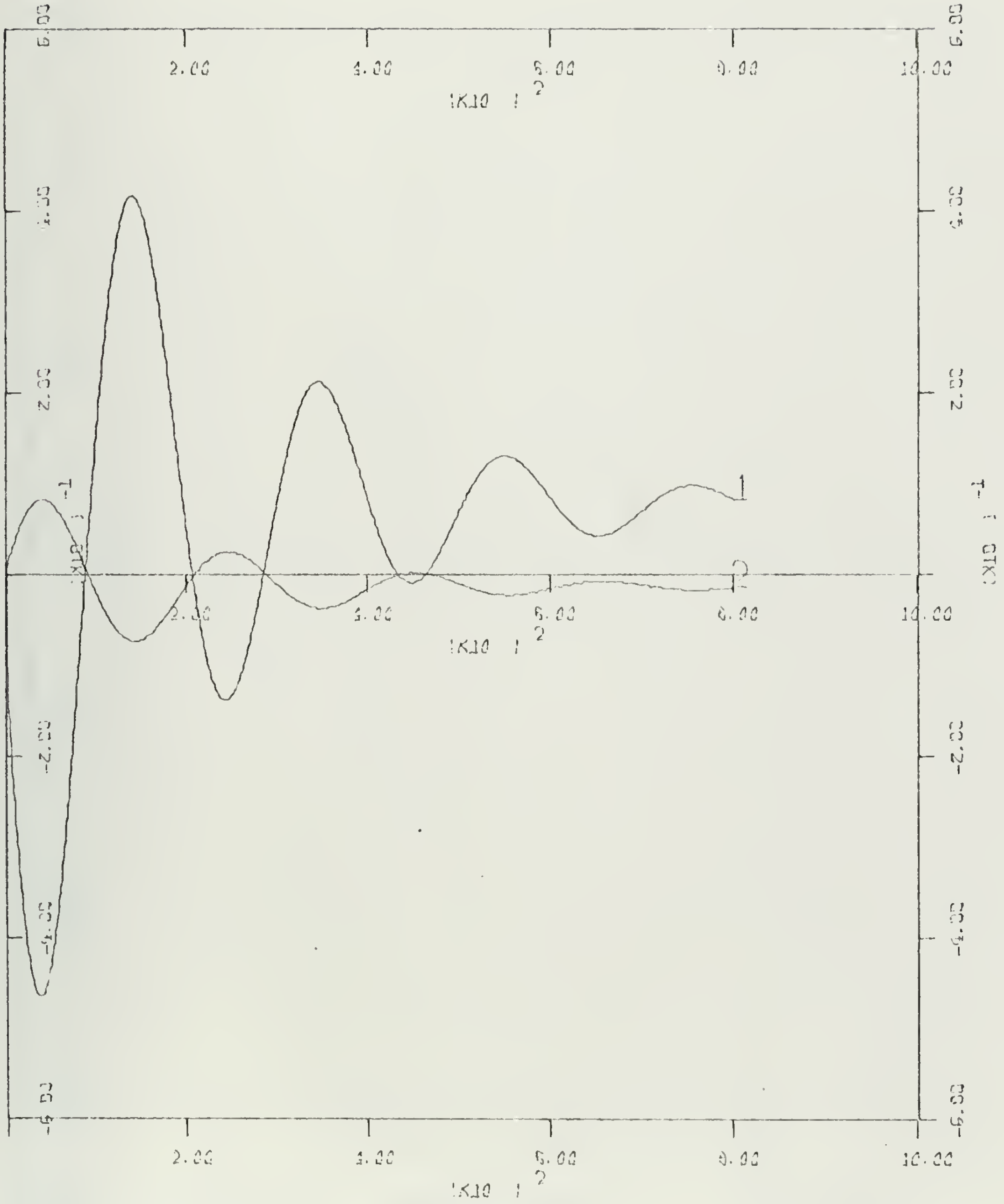


XSCALE=200.00 UNITS/INCH RUN NO.1

YSCALE=0.20 UNITS/INCH PLOT NO.1

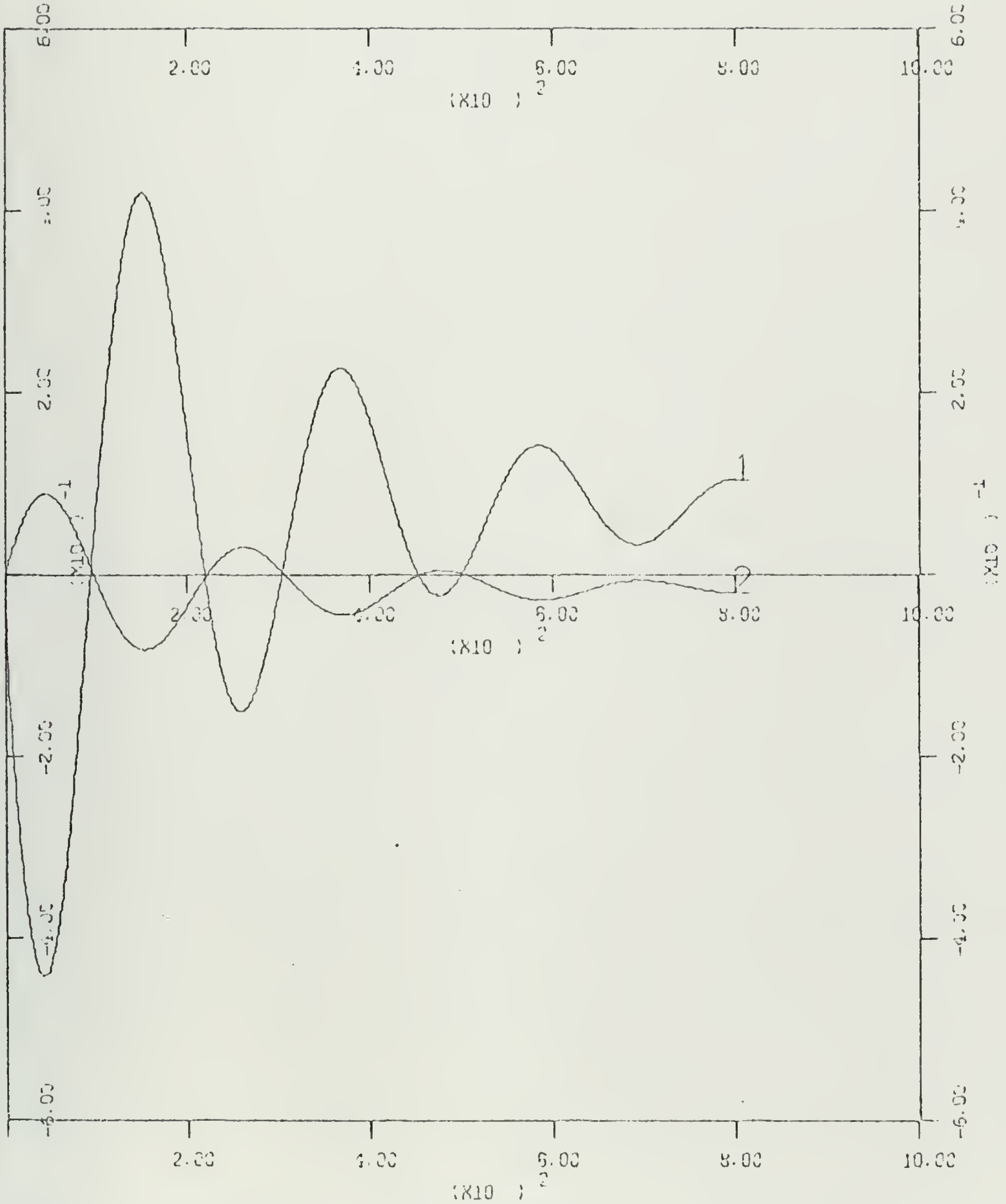
RUDDER ANGLE, THETA VS TIME K1 5.6

AGUAYO FIGURE 54



XSCALE=200.00 UNITS/INCH RUN NO.2
YSCALE=0.20 UNITS/INCH PLOT NO.1

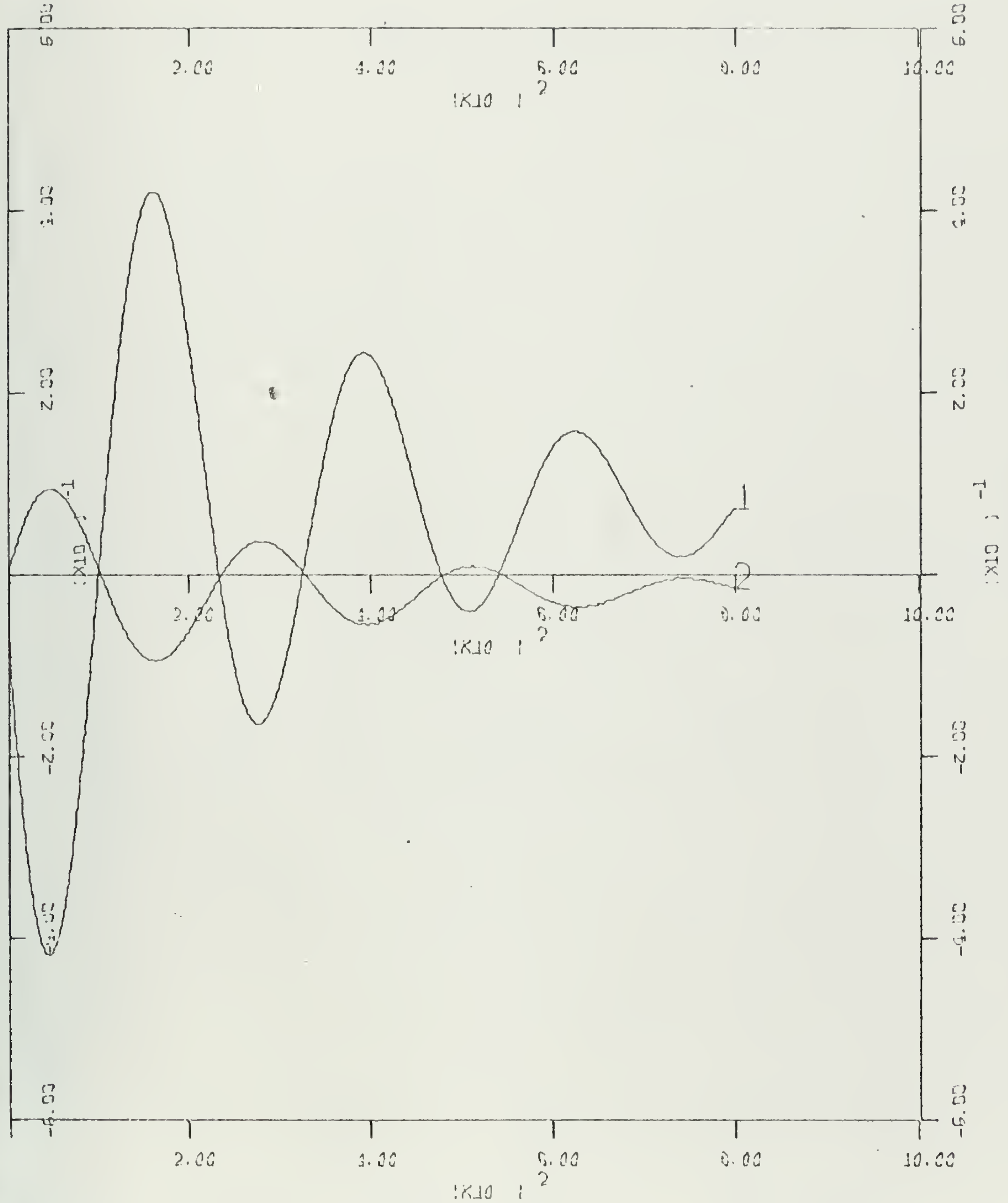
RUDDER ANGLE, THETA VS TIME K1 5.
AGUAYO FIGURE 55



XSCALE=200.00 UNITS/INCH RUN NO.3
YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1 4.4

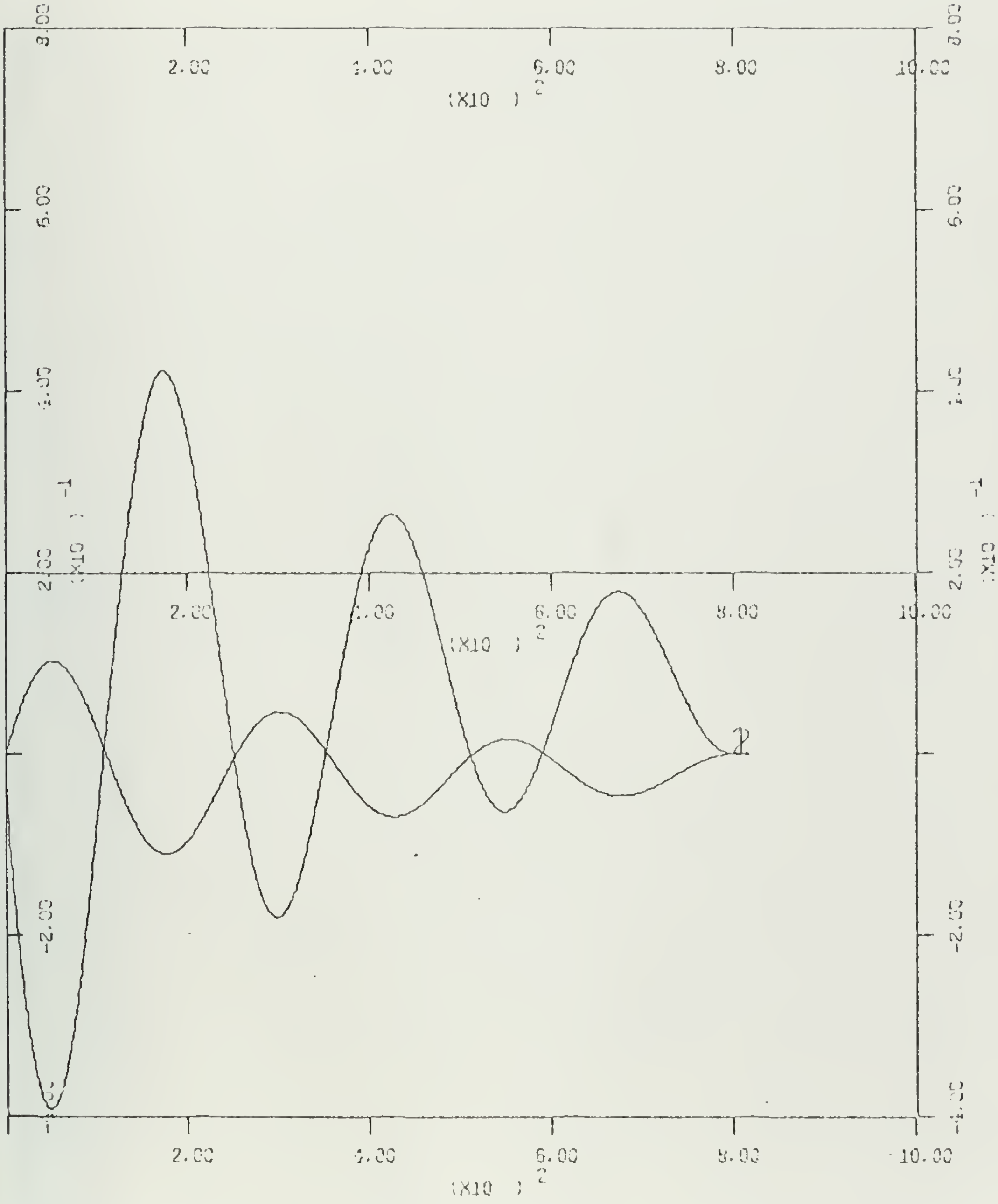
AGUAYO FIGURE 56



XSCALE=200.00 UNITS/INCH RUN NO.4
YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1 3.8

AGUAYO FIGURE 57

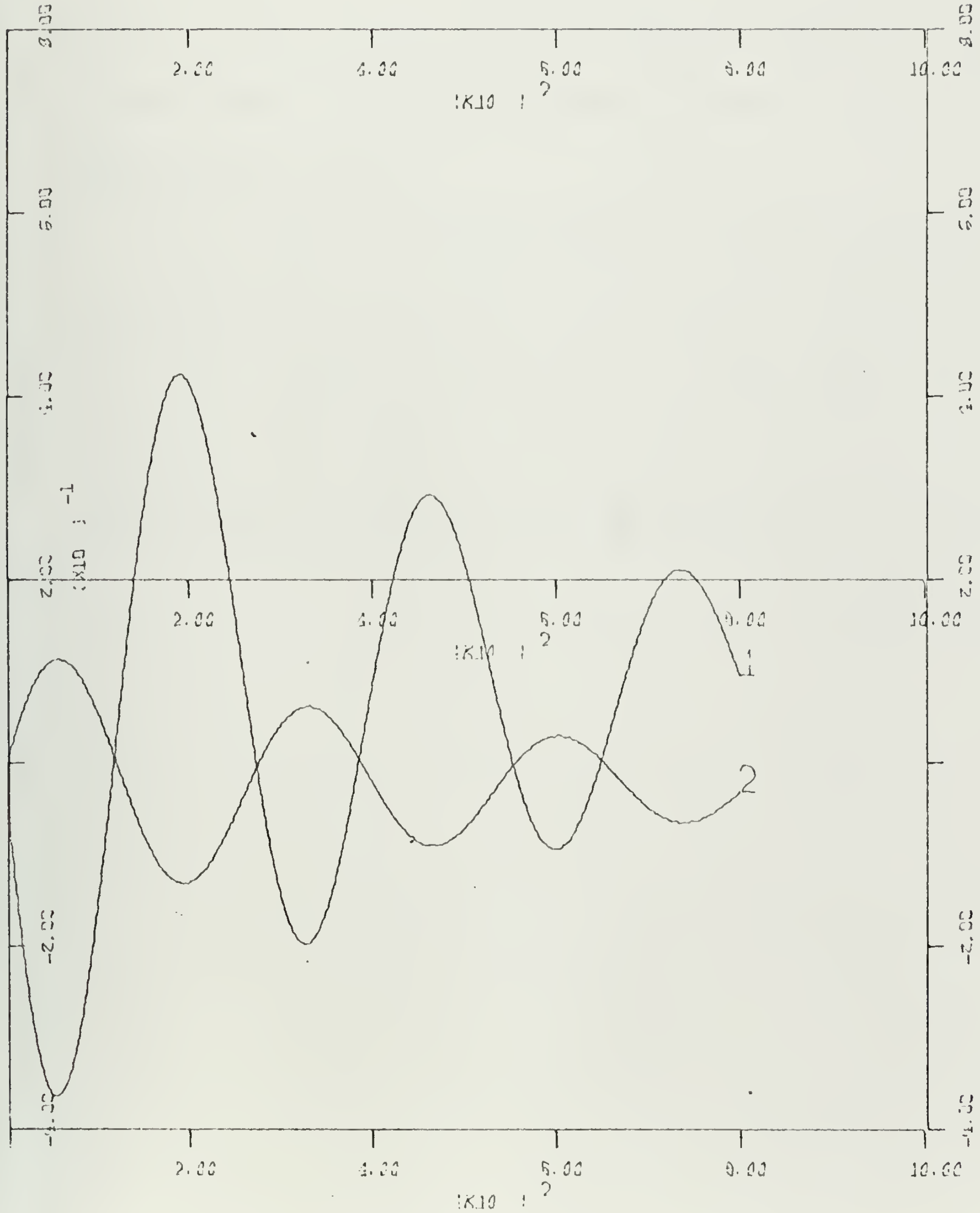


XSCALE=200.00 UNITS/INCH RUN NO.5

YSCALE=0.20 UNITS/INCH PLOT NO.1

RUDDER ANGLE, THETA VS TIME K1 3 .2

AGUAYO FIGURE 58



XSCALE=200.00 UNITS/INCH RUN NO.1

YSCALE=0.20 UNITS/INCH PLOT NO.1

for this system, for gain values of 6.2, 5.6, 5., 4.4, 3.8, and 3.2, following the same considerations as with the Filter. We can see from these figures that in all cases the system has increased its transient, being the best value, 6.2 as observed in figure 53. In the event of increasing the gain to 6.7 we start obtaining clipping in the rudder action, so this value of gain is chosen as the best suited for this type of system.

From comparison between these two systems we can select the one with Filter compensation, first, because of the best final results, i.e., less amount of rudder required, better settling time, and secondly for the reliability of the system, since the Rate Gyro could not be suitable for marine use due to this overhaul interval.

VI. CONCLUSIONS

A. RESULTS

An optimal value of gain can always be obtained using the Root-Locus method for any given plant. Both negative and positive feedback can be used to achieve the desired results but only negative position feedback should be used to obtain a stable system.

With the concepts of Chapter IV, the requirements for a basic Course-Keeping, and our best value for the system selected as the best, we verify with a low order disturbance represented by an initial condition of Θ , that the actual heading in the steady state is equal to the reference heading or which is the same the steady state error is equal to zero. We already have observed that for a load disturbance represented by the step input we obtain a small steady state error. So we have reasons to believe that we are working with a type zero system and, if it is so, do we need to change the loop type number?

By doing an analysis of the feedback loop we can easily verify that indeed we have a type zero system, and using the final value theorem for this linear system, the evaluation of steady state error for the deterministic input is easily accomplished. In this case where steady state error is finite its magnitude is determined by the reciprocal of the gain transfer function for the direct path between

input and output, this magnitude is called an error constant, also called the DC gain or zero frequency gain, because it is the numerical value obtained for the transfer function by deleting the s factors and substituting s = 0. Following this reasoning and with the final results obtained we see that this meets our requirements for the stable operation of the system with the degree of accuracy that can be considered as satisfactory.

The purpose of this thesis, which was to study the basis of the Course-Keeping with Automatic Control, is reached at this stage. It is good to point out that further studies could be made by studying the sea effects, how automatic steering and the yawing of ships is affected in rough seas.

APPENDIX A

LIST OF SYMBOLS

d	draught of a ship, mean of fore and aft if no remark.
I_{zz}	moment of inertia of a ship about a vertical axis through her centre of gravity.
I'_{zz}	$I_{zz}/\frac{\rho}{2}L^4d$
J_{zz}	moment of inertia of additional mass about a vertical axis through the centre of lateral additional mass.
J'_{zz}	$J_{zz}/\frac{\rho}{2}L^4d$
L	length of a ship, between perpendiculars, if no remark.
m	mass of a ship.
m'	$m/\frac{\rho}{2}L^2d$
m_x	longitudinal additional mass.
m'_x	$m_x/\frac{\rho}{2}L^2d$
m_y	lateral additional mass.
m'_y	$m_y/\frac{\rho}{2}L^2d$.
N	hydrodynamic moment about a vertical axis through the C. G. of a ship, positive for standard turning moment.
N'	$N/\frac{\rho}{2}L^2dV^2$
N'_β	$\partial N'/\partial\beta$
N'_r	$\partial N'/\partial r'$
N'_δ	$\partial N'/\partial\delta$
r	yaw angular velocity, positive to starboard, identical with $\dot{\theta}$.

r'	$r/(V/L)$ or L/R
R	turning radius, steady or instantaneous
V	ship speed in meters/second
Y	lateral component of hydrodynamic force, positive to starboard.
Y'	$Y/\frac{\rho}{2} L d V^2$
Y'_β	$\partial Y'/\partial \beta$
Y'_r	$\partial Y'/\partial r'$
Y'_δ	$\partial Y'/\partial \delta$
β	angle of drift, positive to port.
δ	angle of helm, positive to starboard.
$\dot{\Theta}$	turning angular velocity, positive to starboard, identical to r.

APPENDIX B

THE DIEUDONNE SPIRAL MANEUVER

The spiral maneuver consists of the following:

1. The ship is "steadied" on a straight course at a preselected speed and held on this course and speed for about 1 minute. Once a steady speed is established, the power plant controls are not manipulated for the duration of the maneuver.

2. After about 1 minute, the rudder is turned to an angle, δ , of about 15 degrees and held until the rate of change of yaw angle maintains a constant value for about 1 minute.

3. The rudder angle is then decreased by a small amount (about 5 degrees) and held fixed again until a new value of $\dot{\theta}$ is achieved and is constant for several minutes.

4. The foregoing procedure is repeated for different rudder angles changed by small increments from, say, large starboard values to large port values and back again to large starboard values.

The numerical measures obtained from the preceding spiral maneuver are the steady yawing rates as a function of rudder angle. A plot of these values is indicative of the stability characteristics of a ship. For example, if the plot is a single line going from starboard rudder to port and back again, as shown for ship A in figure 1-B, the ship possesses controls-fixed, straight-line stability; that is, it

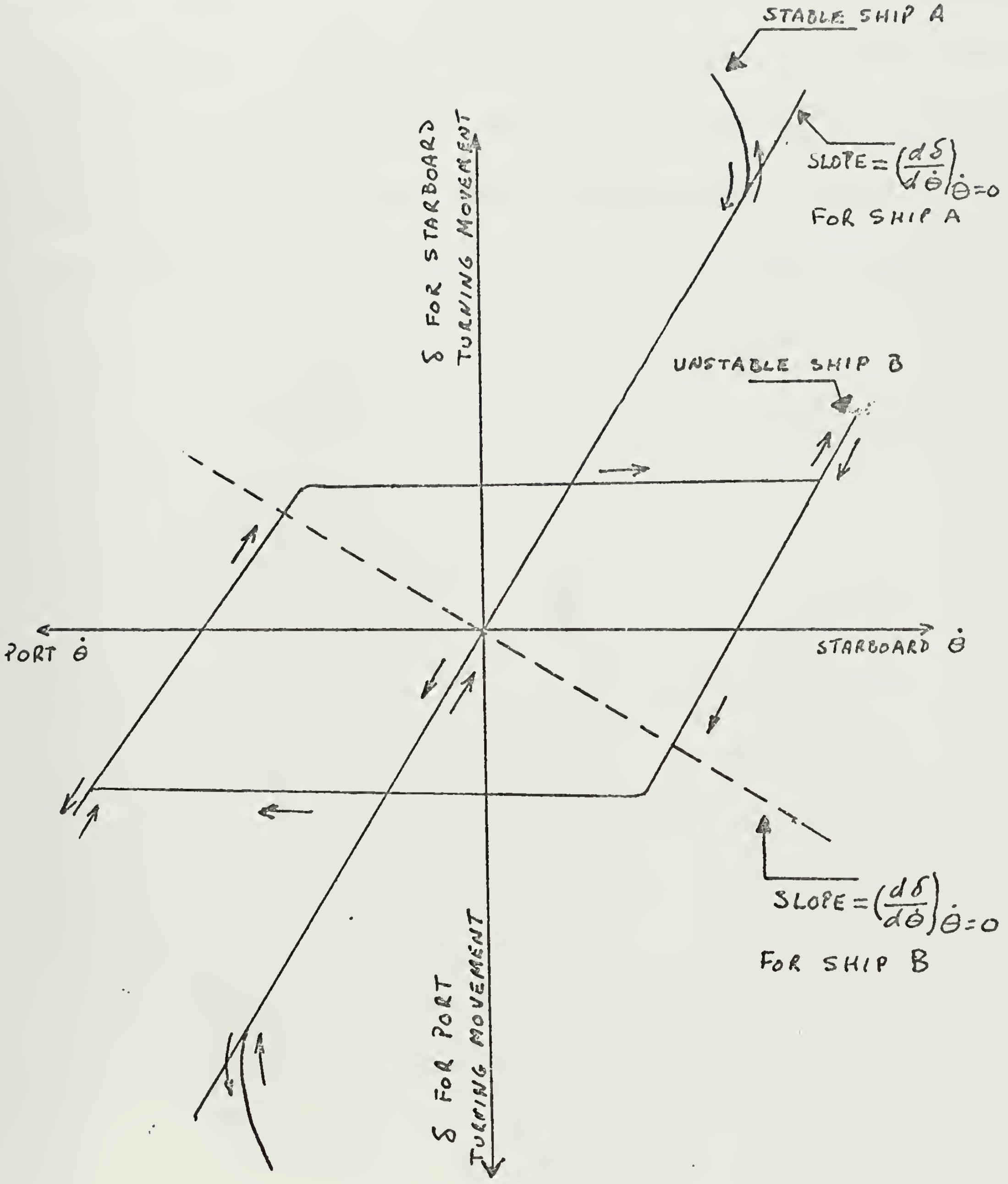

STABLE SHIP A
SLOPE = $\left(\frac{d\delta}{d\dot{\theta}}\right)_{\dot{\theta}=0}$
FOR SHIP A
δ FOR STARBOARD TURNING MOVEMENT
UNSTABLE SHIP B
PORT $\dot{\theta}$
STARBOARD $\dot{\theta}$
SLOPE = $\left(\frac{d\delta}{d\dot{\theta}}\right)_{\dot{\theta}=0}$
FOR SHIP B
δ FOR PORT TURNING MOVEMENT

FIGURE 1-B

has a negative stability index. If, however, the plot consists of two branches joined together to form a "hysteresis" loop, as shown in ship B of figure 1-B, the ship is unstable; that is, it has a positive stability index. In addition, the height and width of the loop are numerical measures of the degree of instability; the larger the loop the more unstable the ship. The slope of the yaw-rate curve at zero rudder angle is a measure of the degree of stability or instability.

```
C       THIS PROGRAM WILL PLOT THE SYSTEM RESPONSE TO A STEP
C       DISTURBANCE. THE BLOCK DIAGRAM OF THE SYSTEM IS THAT
C       REPRESENTED IN FIGURE4. THE VALUES OF GAIN SELECTED
C       ARE THE ONES WITH BETTER TIME CONSTANT FROM THE ROOT
C       LOCUS GRAPH OF FIGURE 5
PARAM   IN1=0.,IN2=1.,K1=12.,K2=-.0434
CONTRL  FINTIM=800.,DELT=.8,DELS=.8
INTGER NUM,NPLOT
CONST  NPLOT=1
DERIVATIVE
        ERROR=IN1-THETA
        DELTAR=K1*ERROR
        DELTA=REALPL(0.,1.7,DELTAR)
        AMPLI=K2*DELTA
        COMP=LEDLAG(0.,20.,-269.3,AMPLI)
        CORREC=REALPL(0.,9.3,COMP)
        THETA1=IN2+CORREC
        THETA=INTGRL(0.,THETA1)
SAMPLE
        CALL DRWG(1,1,TIME,DELTA)
        CALL DRWG(1,2,TIME,THETA)
TERMINAL
        CALL ENDRW(NPLOT)
END
STOP
```

```
C       THIS PROGRAM WILL PLOT THE SYSTEM RESPONSE TO A STEP
C       DISTURBANCE. THE BLOCK DIAGRAM OF THE SYSTEM IS THAT
C       REPRESENTED IN FIGURE 6. THE VALUES OF GAIN SELECTED
C       ARE THE ONES WITH BETTER TIME CONSTANT FROM THE ROOT
C       LOCUS GRAPH OF FIGURE 5
PARAM INI=0.,IN2=1.,K1=12.,K2=-.0434
CCTRL FINTIM=800.,DELT=.8,DELS=.8
INTGER NUM,NPLOT
CONST NPLOT=1
DERIVATIVE
        ERROR=INI-THETA-THETA1
        DELTAR=K1*ERROR
        DELTA=REALPL(0.,1.7,DELTAR)
        AMPLI=K2*DELTA
        COMP=LEDLAG(0.,20.,-269.3,AMPLI)
        CORREC=REALPL(0.,9.3,COMP)
        THETA1=IN2+CORREC
        THETA=INTGRL(0.,THETA1)
SAMPLE
        CALL DRWG(1,1,TIME,DELTA)
        CALL DRWG(1,2,TIME,THETA)
TERMINAL
        CALL ENDRW(NPLOT)
END
STOP
```

```
C       THIS PROGRAM WILL PLOT THE SYSTEM RESPONSE TO A STEP
C       DISTURBANCE. THE BLOCK DIAGRAM OF THE SYSTEM IS THAT
C       REPRESENTED IN FIGURE 34. THE VALUES OF GAIN SELECTED
C       ARE THE ONES WITH THE DAMPING COEFFICIENTS SELECTED
C       FROM THE ROOT-LOCUS DIAGRAMS OF FIGURES 28, 29, 30, 31
C       AND WITH THE LIMITERS FOR THE RUDDER PARAMETERS USING
C       THE EQUIVALENT CIRCUIT OF FIGURE 43.
// EXEC DSL
//DSL.INPUT DD *
PARAM IN1=0.,IN2=.0033,K1=9.42,K2=-.0434,K3=.588,...
      P1=-.0404,P2=.0404,P3=-.52,P4=.52,K4=0.
CONTRL FINTIM=800.,DELT=.8,DELS=.8
CONST SW1=0,SW2=0,SW3=0,FLAG=0,NPLOT=4
INTGER FLAG,SW1,SW2,SW3,NPLOT
DERIVATIVE
      ERROR=IN1-THETA-THETA1*K4
      FILTER=LEDLAG(0.,25.,2.5,ERROR)
      DELREF=FILTER*K1
      ALPHA=DELREF-DELTAC
PROCED ALFA=RUDDER(ALPHA,FLAG,SW1,SW2,SW3,DELTAC,P4)
      ALFA=ALPHA
      IF(ABS(DELTAC).GE.P4)SW1=1
      IF(SW1.EQ.1)ALFA=0.
      IF(SW1.EQ.0)SW3=0
      IF(ALPHA)10,6,6
   10 SW2=1
      GO TO 7
    6 SW2=0
    7 IF(((FLAG.NE.SW2).OR.(SW3.EQ.1)).AND.(SW1.EQ.1))GO TO8
      GO TO 9
    8 ALFA=ALPHA
      SW3=1
    9 SW1=0
      FLAG=SW2
ENDPRO
      DELDOR=K3*ALFA
      DELDOT=LIMIT(P1,P2,DELDOR)
      DELTA1=INTGRL(0.,DELDOT)
      DELTAC=LIMIT(P3,P4,DELTA1)
      AMPLI=K2*DELTAC
      COMP=LEDLAG(0.,20.,-269.3,AMPLI)
      CORREC=REALPL(0.,9.3,COMP)
      THETA1=IN2+CORREC
      THETA=INTGRL(0,THETA1)
SAMPLE
      CALL DRWG(1,1,TIME,DELTAC)
      CALL DRWG(1,2,TIME,THETA )
TERMINAL
      CALL ENDRW(NPLOT)
      GO TO (1,2,3),NPLOT
    3 K1=15.87
      CALL RERUN
      RETURN
    2 K1=23.67
      CALL RERUN
      RETURN
    1 K1=3.5
      CALL RERUN
END
STOP
//PLOT.SYSIN DD *
RUDDER ANGLE, THETA VS TIME  K1=9.42
AGLAYC    FIGURE  39
                                             5.0        6.0
RUDDER ANGLE, THETA VS TIME  K1=15.87
AGLAYC    FIGURE  40
                                             5.0        6.0
RUDDER ANGLE, THETA VS TIME  K1=23.67
AGLAYC    FIGURE  41
                                             5.0        6.0
RUDDER ANGLE, THETA VS TIME  K1=3.5
AGLAYC    FIGURE  42
```

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A ship in steering is considered as a physical mechanism that is forced by a rudder movement to produce a response. Emphasis is laid upon the relation between the forcing and the response, leaving aside any detailed consideration of the forces concerned.

Course-Keeping with Automatic Control techniques is studied following this concept. Computer programs are developed to simulate different conditions. Interpretation of the results is made to evaluate the different methods used.

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